Monitoring the Marine Environment of Long Island Sound at Millstone Nuclear Power Station

Waterford, Connecticut

THREE-UNIT OPERATIONAL STUDIES
1986 - 1987

NORTHEAST UTILITIES
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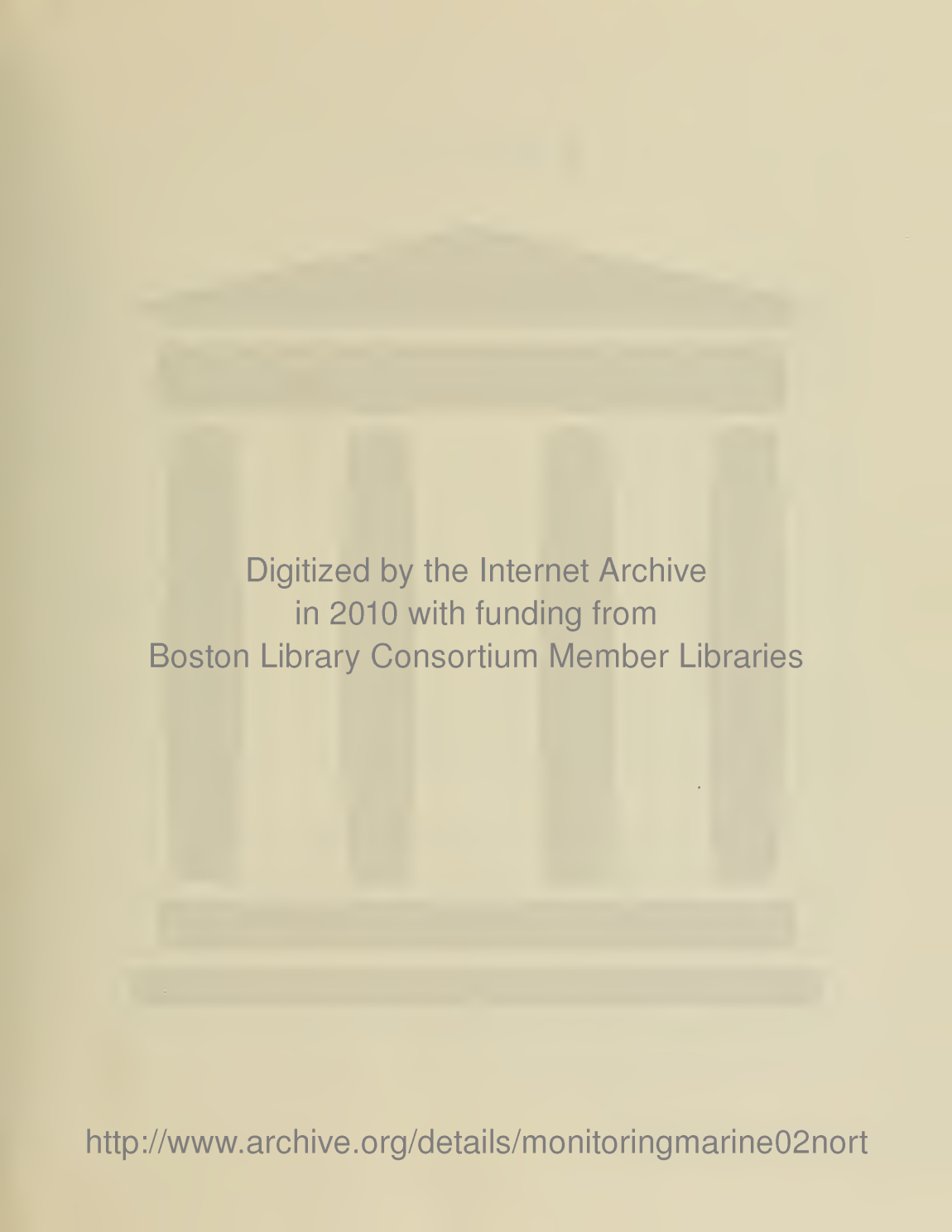
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Executive Summary

Rocky Intertidal Studies

The rocky intertidal sampling program was designed to assess potential biological perturbation from operation of Units 1 and 2 and construction of Unit 3, and to provide base-line data that would permit prediction and assessment of potential impact from Unit 3 operation. Attached plant and animal species on local rocky shores were identified, temporal and spatial patterns of occurrence and abundance of these benthic species were examined, and physical and biological factors that induce variability were identified. This report includes data from the initial 3-unit operational period. Qualitative algal collections, quantitative studies of intertidal organisms, recolonization studies, and *Ascophyllum nodosum* studies were performed to assess impact, and are summarized below.

The local flora, as characterized by qualitative algal collections, has shown consistent spatial and temporal patterns of distribution during MNPS operation. Overall, 160 algal species have been identified since the inception of the monitoring program in 1979, consisting of 75 reds, 40 browns, and 45 greens. In the 3-unit operational period to date, 128 species have been found; 59 reds, 33 greens, and 36 browns. Divisional proportions and seasonal distributions have not changed during 3-unit operation.

Antithamnionella floccosum and *Nemalion helminthoides* have been identified only in the 3-unit operational period, but their occurrence is related to sporadic distribution rather than power-plant operation. Species composition at Fox Island-Exposed under 3-unit operating conditions continues to resemble that found under 2-unit, 2-cut conditions.

Quantitative studies show intertidal zonation patterns typical of rocky shores throughout New England, with the high intertidal dominated by barnacles, the mid intertidal by barnacles and fucoids, and the low intertidal dominated by *Chondrus crispus*, a perennial red alga. The abundances of these major components of local rocky shore communities vary over time and space. Variations are predictable and explainable in terms of seasonality, degree of exposure, intertidal height, inter- and intraspecific competition, and life-history of the organisms. Changes to communities have been minor, indicating stable environmental conditions during MNPS operation.

An exception to the local stability was the development of a community dominated by opportunistic ephemeral algae after the opening of the second quarry cut in August 1983 at Fox Island-Exposed (FE), the station closest to the discharges. This change was attributed to thermal incursion and water temperatures in excess of 28 °C. High water temperatures in late summer 1984 were responsible for the elimination of the perennial algae, *Chondrus crispus*, *Ascophyllum nodosum* and *Fucus vesiculosus* from the low intertidal at FE. *Codium fragile*, a large green alga, became and remains a dominant component of the FE community. However, *Fucus* has recolonized the mid intertidal zone at FE; its persistence is evidence of stability at a new level.

Recolonization studies, performed during 2-unit operation, allowed isolation and identification of some factors that influence the structure of local rocky intertidal communities. Recolonization was influenced by time of year in which denuding occurred, and related to degree of exposure and intertidal height, e.g.,

rapid in the high intertidal of an exposed station and slow in the low intertidal of a sheltered station. Preliminary results from studies re-established during 3-unit operation corroborate those conclusions.

Growth and mortality studies of *Ascophyllum nodosum*, a perennial brown alga sensitive to water temperature change, were included in the rocky intertidal sampling program. Tip length analyses helped distinguish between a stressed population at Fox Island and populations at two reference stations. *Ascophyllum* tip length data, fit to a Gompertz growth function, shows a response to elevated water temperature.

With the exception of the FE intertidal community, no significant changes to the benthic shore biota were observed that could be attributed to MNPS operation.

Benthic Infauna

Intertidal and subtidal infaunal communities in the vicinity of MNPS were sampled during start-up of Millstone Unit 3 and over the first operational year. Power plant-induced impacts were assessed by characterizing communities in terms of community structure and abundance and comparing these data with those collected before Unit 3 start-up.

Intertidal infaunal communities exhibited spatial patterns in community abundance and composition and seasonal fluctuations in abundance that were consistent with those observed during the base-line period. Higher infaunal abundances and number of species continued to occur at Jordan Cove (JC), while communities at White Point (WP) and Giants Neck (GN) generally included lower numbers of individuals and species. At the population level, the JC community continued to be dominated by oligochaetes while *Paraonis fulgens*, *Haploscoloplos fragilis* and rhynchocoels dominated the WP and GN communities.

Although spatial patterns among intertidal stations were consistent between pre-operational and operational periods, there were temporal changes in community abundance and species composition evident at all sampling stations. Many of these differences appeared to be continuations of trends which were first evident before Unit 3 operation commenced, suggesting that observed declines were a response to some regional event. At JC, reductions in total abundance and species number were also evident, but they were not as extensive as those at GN and WP. There were, however, unusually low densities of *Scolecolepides viridis* and *Hediste diversicolor* in June 1987. Low densities of *Scolecolepides viridis* were also evident at GN in June 1987, indicating a possible area-wide decrease. Sampling intertidal communities during 1986-87 revealed no immediate changes to these communities which could be directly attributed to Unit 3 start-up or to 3-unit operations at MNPS. Possible power plant impacts related to temperature could not be assessed in this report, given the limited 3-unit operational period.

At subtidal stations, Unit 3 start-up resulted in scouring of bottom sediments at Effluent (EF), located immediately offshore from the discharge cut. Along with sedimentary changes, we observed reductions in macrofaunal density and in particular, number of species. At the species level, lowered abundances of *Polycirrus eximius*, *Aricidea catherinae*, oligochaetes, *Tellina agilis*, *Tharyx* spp. and *Lumbrineris tenuis* were recorded and attributed to a reduction in silt/clay content. Power plant-related impacts were also evident at JC after 3-unit start-up and included a substantial increase in silt/clay attributed to the transport and settling of sediments scoured from the area of the Unit 3 discharge cut. Concurrent with this sediment change, there was a significant increase in the abundance of *Mediomastus ambiseta* along with a decline in the abundance of some previously dominant polychaetes *Aricidea catherinae* and *Polycirrus eximius* and oligochaetes. The Intake (IN) area also exhibited changes in sediments and infaunal communities during the operational period. Silt/clay values during 1987 were generally lower than those in recent years and

may be reflecting increased scour during 3-unit operations. The infaunal community in 1987 exhibited significant increases in the abundances of the amphipods, *Ampelisca* spp., *Leptocheirus pinguis* and *Uniciola irrorata*. These organisms were among the dominants at this station prior to the power plant-induced shifts observed following Unit 3 intake construction. Their return is believed indicative of the continued recovery of this community.

Power plant-related impacts on subtidal communities during the first year of 3-unit operation appeared to be a response to scouring (at EF and IN and the transport and deposition of this sediment into JC. Infaunal habitats immediately beneath the Unit 3 discharge (and extending seaward approximately 100 m) have been eliminated due to scouring by the 3-unit discharge; however, given the limited size of this area, loss of this infaunal habitat would not significantly alter ecosystem functioning in the greater Millstone area. At JC, the deposition of sediments apparently from the discharge area would be expected as a temporary change. Infaunal changes related to this siltation should also be temporary and cause no detectable changes in the ecology of the Millstone area. If however, the sedimentary changes are the result of some plant-induced change in the sedimentation patterns in JC or the infaunal shifts were a response to temperature, then more widespread and ecologically significant changes in local infaunal communities might occur. Given limited operational history, impacts due to temperature could not be identified separately from those which occurred in response to sediment changes.

Lobster Population Dynamics

The lobster population in the Millstone Point area was sampled from May through October during 1986 and 1987 using wire pots set at three stations. The carapace length, sex, presence of eggs, missing claws and molt stage was recorded for each lobster to quantify population characteristics. Lobsters > 55 mm carapace length were tagged and released where they were caught to monitor growth and movement. Studies were also conducted on adult lobsters caught on the intake traveling screens (impingement) and on larval lobsters drawn through the plants cooling water system (entrainment). All these studies were designed to assess the impacts of 3-unit operation on the local lobster population.

Total catch per unit effort (CPUE; #lobsters/# pots hauled) during 1986 and 1987 was 1.70 and 1.72, respectively, and within the range of values reported during 2-unit operations (0.85-2.10). Legal CPUE was lower during 1986 and 1987 (0.097, 0.089) when compared to previous years' results and has significantly declined since 1978. The lower CPUE of legal-sized lobsters may be related to fishing pressure which has increased in Long Island Sound since 1978. A 50% decline in catch at Jordan Cove occurred from August to September 1986 and was related to 3-unit operations. Sediments in the discharge area were scoured and subsequently deposited in Jordan Cove, where lobster habitats were buried by sediments. This decline in catch was only temporary, since catches in October 1986 and throughout 1987 at Jordan Cove were normal and indicated that sediments had stabilized and lobsters had returned to the affected area. Similar impacts associated with the disruption of lobster habitat were observed in previous years following dredging in the vicinity of the intake structures.

The mean size of lobsters caught during 3-unit operation was 70.1 mm in 1986 and 70.2 mm in 1987. These values were smaller than those reported in previous years (range 70.7-71.8 mm) due to the lower CPUE of legal-sized lobsters during 1986-87. Male to female sex ratios during 1986 and 1987 were 1.0:0.87 and 1.0:0.88, respectively, and within the range of values reported during 2-unit studies. The Twotree station continued to yield a higher proportion of females than the other two nearshore stations, a trend consistent since the study began. Female size at sexual maturity was similar during 2- and 3-unit operations; females began to mature between 50 and 55 mm CL and all females were mature at sizes greater than 95

mm CL. The mean CL of berried females during 1986 (78.0 mm) and 1987 (76.5 mm) and the proportions of sublegal size berried females caught in 1986 (75%) and 1987 (90%) confirmed the small size at first sexual maturity of females in the Millstone area.

Lobsters that were near molting comprised 3.2% and 3.0% of the 1986 and 1987 total catches, respectively, which were within the range of values reported during 2-unit operations. Growth per molt averaged 13.3% in 1986-87 compared to 13.9% from 1978-85. The percentage of lobsters missing one or both claws (culls) in 1986 (10.6%) and 1987 (10.3%) was lower than the average percentage culled in previous years (range 10.6%-15.5%) due to the implementation of the escape vent regulation in 1984.

The numbers of lobsters tagged in 1986 (5,698) and 1987 (5,680) were within the range of annual values for lobsters tagged in pre-operational studies. Recapture rates for 1986 (21.0%) and 1987 (23.9%) were also similar to pre-operational values (range 15.9%-23.9%). Lobstermen recaptured 20.2% of our tagged lobsters in 1986 and 17.8% in 1987. Lobster movements were localized, since 94% and 97% of all commercial recaptures were made within 8 km of Millstone Point during 1986 and 1987, respectively. Several lobsters moved outside LIS and were caught in waters off RI and MA; three lobsters moved offshore during 1986-87, where they were caught in deep water canyons on the edge of the continental shelf.

Lobster larvae densities (number per 1000 m^3) in entrainment samples were higher in 1986 (0.88) and 1987 (0.63) when compared to 1984-85 (0.42-0.43). The estimate of total lobster larvae entrainment, based on sample density and total MNPS cooling water demand, was also higher in 1986 (548,635) and 1987 (304,694) when compared to 1984-85 (79,511-138,820). Lobster larvae survival was 6.5% and 3.8% in 1986 and 1987, respectively. More stage IV larve were collected in 1986 compared to 1984, 1985, and 1987 when greater numbers of stage I larvae were collected.

The estimated numbers of lobster impinged at Unit 2 during 1986 and 1987 were 676 and 825, respectively, these values were within the range of values reported in previous years (261-1220). Fish return systems at Units 1 and 3 improved overall survival of impinged lobsters. Based on impingement of all organisms at Unit 2 since 1972, a request made by NUSCO to discontinue impingement monitoring at Unit 2 was accepted by the CT DEP in December 1987.

There is no evidence to date that MNPS has significantly affected the local lobster population. The displacement of lobsters in Jordan Cove due to scouring of sediments in the discharge area was temporary and related to the intial period of simultaneous 3-unit operation. Impacts on larval lobsters entrained through the MNPS cooling water systems will not be apparent in the adult population until 4-5 years when they grow to a size vulnerable to capture in our traps.

Winter Flounder Studies

The life history and population dynamics of the winter flounder (*Pseudopleuronectes americanus*) have been intensively studied since 1973 due to its importance to the sport and commercial fisheries of Connecticut. Because of the localized nature of winter flounder stocks, the population closest to MNPS, which spawns in the Niantic River, has received most of our attention.

Indices of abundance estimates are available from 1976 through 1987 for the adults spawning in the Niantic River. These include a Jolly composite abundance index and median trawl CPUE, both computed from data collected during annual mark and recapture surveys. The 1987 Jolly index showed a slight increase over the 12-year low value found in 1986, but abundance remained low in comparison to earlier years.

The median CPUE also increased relative to 1986 and was similar in magnitude to those for 1984 and 1985. However, this abundance index was only 30 to 60% of the estimates for 1976 through 1983.

Annual median CPUE was also determined for juveniles (< 15 cm) taken in the Niantic River during the adult population abundance surveys. Juvenile catches were more variable than those of adults. Comparatively low medians were found in 1986 and 1987, which suggested poor reproductive success in recent years. However, factors such as differential distribution within the river among the years most likely affected the reliability of this index of abundance.

The winter flounder was the most common fish taken in the trawl monitoring program (TMP). Annual TMP δ-mean CPUE values were computed for the first time for all winter flounder taken each year from 1976 through 1986. The pattern of annual δ-mean abundances differed from that for the Niantic River median CPUE values. The peak in δ-means persisted from 1977 through 1983, but was not as pronounced as it was for the Niantic River medians, which were highest in 1981 and 1982. The δ-means for 1985 and 1986 were greater than those in 1977 and 1978, while the Niantic River median CPUE in recent years indicated lower abundance than during the 1970s.

About one-half to three-quarters of the fish taken by the TMP were larger than 15 cm. However, small (< 15 cm) fish made up about two-thirds of the total from January through April as larger fish congregated on the spawning grounds. Catch of smaller fish outside of the Niantic River as measured by the δ-mean fluctuated less than the corresponding median CPUE. This suggested that juvenile abundance may not have been as low as recent catches in the Niantic River surveys indicated.

Both the annual Niantic River median CPUE and the TMP δ-means were compared to other regional indices of abundance, including two commercial fishing CPUE for Rhode Island and one for Connecticut and a University of Rhode Island research trawl time-series. With a few exceptions, most indices were significantly correlated and thus described real trends in abundance that occurred throughout Southern New England. Examination of the Rhode Island historical time-series showed that winter flounder abundances have typically fluctuated over time. Sharp increases in catches were most likely related to occurrences of particularly large year-classes. Recent declines in winter flounder populations have reduced abundance to levels at or below those found in the early 1950s and early 1970s.

The sex ratio of winter flounder spawning in the Niantic River over the past 11 years was 1.33 females for every male. However, during the past 2 years more males than females were taken. The length of females at 50% sexual maturation was 26.8 cm, which corresponded to a fish 3 or 4 years old. Spawning in the Niantic River was usually completed by late March or early April and appeared to have been related to water temperature, with proportionately fewer females spawning earlier during colder years. Based on the abundance indices of females and their size distribution, annual indices of egg production were determined. This index peaked in 1982 and has declined about 80% since then. However, as shown below, adult abundance and absolute egg production alone were not the only factors in determining reproductive success.

A stock and recruitment relationship for Niantic River winter flounder was determined using the 12 years of abundance and life history data with the Ricker model. For each year, parental stock was defined as all winter flounder age 3 and older and recruits were those fish turning 3 years old each spawning season. The two-parameter Ricker model only explained 44% of the variability seen in annual recruitment, with large differences in year-class strength seen for similar-sized parental stocks. Annual February water temperature deviations from a long-term mean were found to have been significantly and inversely correlated

with recruitment indices. The addition of a temperature parameter to the model resulted in a much improved fit to the observed data ($R^2 = 0.78$). Although the actual mechanisms affecting winter flounder recruitment were unknown, the February water temperature appeared to have been related to and served as a good measure of those factors.

Larval winter flounder studies have been conducted in Niantic River and Bay since 1983 and entrainment data are available from 1976 through the present. During 1986 and 1987, abundance peaked first in the river and then in the bay, which was similar to previous findings; the lag in dates corresponded to flushing rates in the river. Most larvae entering the bay from the river were in Stage 2 of development.

Greater mortality of larvae occurred in 1987 than 1986, largely early in the season when most larvae were in the river. The effect of jellyfish predation was not as apparent during the past 2 years as it was during 1983-85. Examination of length-frequency distributions indicated that most mortality occurred during the 3 to 4-mm size-class, suggesting that this was a critical period for mortality. Annual total larval mortality rates, based on the difference in abundance between the 3- and 7-mm size-classes, ranged from 84.6 to 96.9%.

Most larvae entrained were in Stage 3 of development. As expected, total entrainment estimates for 1987 following the start-up of MNPS Unit 3 were among the highest during the last 12 years, even though the median density (number per 500 m^3) was among the lowest. Entrainment estimates were dependent upon plant operating conditions as well as larval densities each year. Dates of peak abundance for entrainment samples were positively correlated with March and April water temperatures. From the 12 years of entrainment data, the shape of the abundance curve, as measured by the κ parameter of the Gompertz function, was found to be a good predictor of subsequent recruitment of age 3 winter flounder. The shape of the abundance curve was related to February water temperatures, with a narrow, high-peaked curve found during warmer years (low recruitment) and a broad, flatter curve during colder years (high recruitment).

Laboratory studies showed that larval growth rates were dependent upon water temperature. Of the four temperature regimes examined, optimum temperatures for growth were intermediate (6.9 and 7.5°C), with decreased growth occurring at lower (5.4°C) or higher (10.8°) temperatures. Annual growth rates estimated for 1983-87 using field data collected at Station C in the Niantic River and for 1976-87 using entrainment data were consistent with the findings based on the laboratory data. Again, growth was found to be dependent upon water temperatures.

Post-larval young-of-the-year winter flounder have been collected at two stations in the Niantic River since 1983. Densities at Station LR were higher in 1987 than in previous years. Smaller differences were found in growth of young at both stations in 1986 and 1987 than during 1984 and 1985. Differences among years may have been due to density-dependent growth, especially at LR. Survival rates were very similar among years, regardless of densities of young.

The winter flounder was the second-most abundant fish impinged on the traveling screens at MNPS since 1976. However, relatively few specimens were taken at Unit 2 during the past 3 years because of declining abundance, varying plant operations, and possible reductions related to the construction and operation of Unit 3. The installation of fish return sluiceways at Units 1 and 3 has lessened the impact of impingement on the winter flounder because it has good (> 85%) survival when returned to the water. Routine impingement monitoring at Unit 2 was discontinued in December 1987 upon agreement between NU and CT DEP.

To predict the long-term effects of larval entrainment at MNPS, an impact assessment model for winter flounder is currently under development, which includes hydrodynamics and population dynamics submodels. The function of the submodels is the estimation of the fraction of total larval production lost to entrainment at the plant and the measurement of any resulting population changes, respectively. A newer, more accurate and detailed hydrodynamics submodel is under development at the Massachusetts Institute of Technology. Larval behavior will be simulated to correspond more realistically to observations made in the field. A stochastic age-structured population submodel will incorporate the three-parameter stock-recruitment relationship, which includes a measure of compensatory mortality and the introduction of realistic environmental variability.

Results from both larval analyses and the three-parameter stock-recruitment relationship showed that year-class strength was related to events in the early life history stages, with colder winters associated with better reproductive success. Greatest winter flounder mortality took place during Stage 2 of development, during which density-dependent mortality probably occurred.

Exposure Panel Program

The Exposure Panel Program was designed to assess the effect of Millstone Nuclear Power Station (MNPS) on the abundance and distribution of marine woodborers, and the associated rate of wood-loss. To achieve this objective, fouling organisms, woodborer densities and wood-loss are being monitored at five dock sites and three thermal plume sites (100, 500 and 1000 m from the quarry discharge). Results presented in this report cover the initial period of 3-unit operation and provide a comparison to data collected during 2-unit operation.

The fouling community on wooden exposure panels showed no clear response to 3-unit operation, but this community has correlated negatively with shipworm recruitment throughout the study. Fouling assemblages continue to be diverse, and the abundance and distribution of the component species remain patchy. Patterns of abundance and distribution of several prevalent fouling species were consistent between 2-unit and 3-unit operational periods, i.e., *Cryptosula pallasiana* and *Laminaria saccharina* at sites not influenced by the undiluted thermal plume and *Mytilus edulis* within the undiluted plume. Changes in the densities of juvenile barnacles and *Balanus crenatus* between the two operational periods were attributed to a slightly later set during the 3-unit operational period. The large percentage of cover and density of *Balanus balanoides*, an intertidal barnacle on subtidal panels during 1986 and 1987, were similar to incidental occurrences reported for this species in 1970 and 1971.

Shipworm densities showed the most consistent differences between 2-unit and 3-unit operation. During the first six-month collection period of 3-unit operation (May to November 1986), there was an increase in density of the shipworm, *Teredo navalis*, and an increase in the amount of wood-loss at the White Point and Fox Island sites. At our reference site, Giants Neck, shipworm density decreased. The largest increases in shipworm densities and wood-loss occurred in panels at our undiluted effluent sites during 3-unit operation. These increases were caused by *Teredo bartschi*, a non-native species collected at effluent sites since 1975. The reason for this change is unclear. Because water temperatures at our effluent sites remain very similar between 2-unit and 3-unit operating conditions, some other mechanism was responsible for these observed increases. Possibly, altered water circulation patterns in the effluent quarry allowed more larvae to reach these panels, which were suspended more than 1 m above the bottom.

Panels placed at 100, 500, and 1000 m from the quarry cuts showed decreased recruitment of *T. navalis* at increasing distances from the quarry cuts. This was consistent with past results. *Teredo bartschi* was

collected in panels at 100 m during 2-unit operation, but was not sampled during initial 3-unit operation because the 100 m panels, which were exposed during May to October, were tampered with by people fishing from boats. *Teredo bartschi* was not collected at 500 or 1000 m during either 2-unit or 3-unit operation at MNPS.

In conclusion, since Unit 3 began operation, increased shipworm abundance and increased wood-loss were observed at sites in the MNPS effluent, and during one exposure period, at White Point and Fox Island, which were potentially exposed to the 3-unit thermal plume. Further monitoring will be required to determine whether these changes are related to 3-unit operation, or are expressions of natural variability.

Fish Ecology Studies

The operation of MNPS could affect fish assemblages in the Millstone area by increasing mortality at various life history stages (eggs and larvae may be entrained and juveniles and adults may be impinged), or by altering the thermal environment such that the spatial distributions of some fishes change. The report this year emphasizes the comparison of data collected during 2-unit operations to those collected since the start-up of Unit 3.

Impingement monitoring at Unit 2 was discontinued on December 11, 1987 because losses were well-documented and all feasible mitigative measures had been investigated. Significant declines in total impingement were found in recent years, which were attributed to physical changes near the Unit 2 intakes and possible changes in water circulation patterns because of the operation of Unit 3. Losses due to impingement by MNPS were reduced with the installation of fish return sluiceways at Units 1 and 3.

Over 100 fish taxa have been collected in the demersal trawl, shore-zone seine, impingement, and ichthyoplankton sampling programs since 1976. Eight of these taxa were selected for detailed examination due to their prevalence in entrainment or impingement collections or their abundance in the shore-zone area of Jordan Cove, an area which may be impacted by the thermal plume.

The American sand lance was primarily collected as larvae and was a dominant entrained taxon. A decline in larval abundance has occurred since the early 1980s. This decrease was found throughout the region and included the abundance of adults. The decline in larval abundance in the Millstone area was attributed to this area-wide decrease in adult stock size.

All life history stages of anchovies were very abundant in most of the sampling programs. Adults were present in impingement collections, juveniles were caught by trawl, and eggs and larvae were abundant in entrainment samples. The number impinged declined in recent years, as it has for most species. Based on differential survival from egg to larval stages which was dependent upon initial densities, compensatory mortality was apparent in its early life history. This may mitigate losses of these life stages due to entrainment at MNPS.

Sticklebacks and Atlantic tomcod were primarily found in impingement samples. The impact of MNPS impingement on sticklebacks has been reduced due to high ($>70\%$) survival of individuals returned by sluiceways at Units 1 and 3. There was a marked decrease in Atlantic tomcod numbers impinged at Unit 2 since the start-up of Unit 3. This species also exhibits naturally wide fluctuations in numbers because of its reproductive strategy.

Silversides dominated the shore-zone area of Jordan Cove and adults were abundant in winter trawl and impingement collections. There was a recent decline in the number impinged at Unit 2 that was not evident in the number caught by trawl. No apparent changes occurred in length-frequency distribution or seasonal abundance in Jordan Cove related to the 3-unit thermal plume.

Grubby larvae were present in ichthyoplankton collections and juveniles and adults were taken in trawl and impingement collections. Larval abundance declined in recent years to levels similar to those of the late 1970s. Numbers impinged at Unit 2 have decreased in recent years, most likely due to physical changes near the intake and because of the start-up of Unit 3. Individuals returned by the Units 1 and 3 sluiceways had high survival (> 74%). Except for recent years at the Niantic River station, no long-term changes were found in the mean length or in abundance indices of adults collected by trawl.

The tautog is an important recreational fish in the Millstone area and the greatest potential impact of MNPS on it is through the entrainment of eggs. Egg abundance, the best index of adult stock size, increased in recent years, but larval densities declined to levels similar to the late 1970s. An apparent low egg to larval survival was found in all years examined. Because the tautog takes 2 to 4 years to reach maturity, the possible impact of entrainment by 3-unit operations on adult stock size will not be evident for several years.

Abundances of all life history stages of cunner collected near MNPS have recently declined. In 1986, the numbers of eggs and larvae were among the lowest found since 1976. Decreases in the trawl catch were evident at stations closest to MNPS. Part of the declines in both impingement and in juvenile and adult abundance at a station near the intakes could have been caused by physical changes to the habitat, but reasons for the decline at other stations are not known. The apparent low egg to larval survival in all years was significantly correlated with that for the tautog, suggesting similar factors affecting their reproductive success. Monitoring will continue to determine if the recent decrease in the cunner population was due to a natural fluctuation in abundance or from the operation of MNPS.

Hydrothermal Studies

During 1987 the extent and configuration of the 3-unit thermal plume were determined during various tidal regimes. A dye survey was conducted on 26 August 1987 and supplemental temperatures were recorded by automatic data loggers, which were deployed during October. The configuration and extent of the thermal plume produced during 3-unit operation, as measured by dye concentration, generally matched predictions during all four tidal regimes. Water temperatures recorded continuously at selected locations were also generally what was expected, based on predictions. The plume is highly dynamic and those regions influenced by increased water temperatures generally experienced a respite from warm water for at least several hours during a tidal cycle. Based on both the survey and supplemental temperature data, at no time during the study period did the 4°F (2.2°C) isotherm appear to extend past the 8,000-ft (2,439 m) limit imposed by the NPDES permit. Based on dye concentrations at Unit 1 intakes, very little recirculation of discharge water occurs.

Preface

This report was prepared by the Northeast Utilities Service Company Environmental Laboratory (NUEL) staff. All contributors are acknowledged according to their respective disciplines:

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This report is dedicated to the memory of Bette Fields.

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Introduction

In accordance with Section 221-430 of Chapter 446k of the Connecticut General Statutes and Section 402b of the Federal Water Pollution Control Act, Northeast Nuclear Energy Company (NNECO) was issued a National Pollution Discharge Elimination System (NPDES - CT0003263) permit regulating the discharge of cooling water to Long Island Sound (LIS) from Millstone Nuclear Power Station (MNPS). Paragraph 5 of this permit, issued by the Connecticut Department of Environmental Protection (CT DEP) states that

> *The permittee shall conduct or continue to conduct biological studies of the supplying and receiving waters, entrainment studies, and intake impingement monitoring. The studies shall include studies of intertidal and subtidal benthic communities, finfish communities and entrained plankton and shall include detailed studies of lobster populations and winter flounder populations.*

Further, paragraph 13 of the permit requires that

> *On or before April 30, 1986 and annually thereafter, submit for the review and approval of the Commissioner a detailed report of the ongoing biological studies required by paragraph 5 and as approved under paragraph 12.*

The present report satisfies this NPDES reporting requirement, and provides summaries of the ongoing biological monitoring studies conducted by Northeast Utilities Service Company (NUSCO) and contractor personnel on behalf of NNECO at MNPS during calendar years 1986 and 1987. During this period combined three-unit operations occurred for the first time. Referenced frequently throughout this report are data collected prior to 1986 (see NUSCO 1987), which serve as the baseline against which potential effects of three-unit operation can be compared.

The goal of the MNPS monitoring program, established in 1968, has been to characterize the various estuarine communities in the vicinity of MNPS and determine if station construction and operation have resulted in changes beyond those that would be expected to occur naturally. To accomplish this goal, various investigations have been conducted. Early biological investigations included exposure panel monitoring of fouling communities and surveys of intertidal sand and rocky shore communities and shore-zone fish assemblages. The scope was expanded between 1970 and 1973 to include impingement and entrainment monitoring, surveys of pelagic and demersal fish assemblages, plankton and subtidal benthic communities and studies of lobster and Niantic River winter flounder population dynamics (NUSCO 1987). In addition, numerous hydrographic studies have been conducted for the purpose of thermal plume mapping and predictive modeling. Tidal circulation models were also developed to refine thermal plume predictions and to model dispersal of larval winter flounder. A detailed discussion of early studies was provided by NUSCO (1987).

The Study Area

The MNPS is located on the southeastern coast of Connecticut in the Town of Waterford, approximately 8 km west southwest of New London (Fig. 1). The approximately 500-acre site is situated on Millstone Point, a peninsula in the eastern part of LIS that is bounded on the west by Niantic Bay, on the east by Jordan Cove and on the south by Twotree Island Channel. The LIS estuary is approximately 82 km long and 40 km wide with an average depth of 19 m (Nixon 1983). Because the average tidal excursion in LIS

is about 1.5 m, the tidal exchange is about 2 x 10^5 m^3/s, which over a 12.5-hr tidal cycle, produces strong tidal currents (3 - 5 knots) in the Race, the geographic feature through which most tidal flushing of LIS occurs (NOAA 1987).

The MNPS monitoring program covers an approximately 50-km^2 study area 2 km west of Black Point, 2 km south of Twotree Island and 2 km east of White Point (Fig. 1). In this area, water depth varies, reaching 15 m in Twotree Island Channel and up to 20 m in one area southwest of Twotree Island. The bottom throughout the study area is generally composed of fine to medium sand but includes some rock outcrops and muddy-sand in nearshore areas (NUSCO 1975c).

The tides in the study area have a mean and spring range of 0.8 and 1 m, respectively (NOAA 1987). Because of the Station's proximity to the Race, tidal currents dominate natural water movement in the area. In particular, the flow into and out of Niantic Bay forms a strong current past MNPS along a line running from the site through Twotree Island Channel. Currents in Twotree Island Channel are on the order of 1 to 1.8 knots and currents passing the Station are on the order of 1 to 1.5 knots (NUSCO 1975b) which produces a tidal exchange in Niantic Bay of 2.8 x 10^3 m^3/s. In contrast, currents in Jordan Cove, even during the strength of ebb and flood tides are relatively weak (NUSCO 1975b).

The salinity in LIS ranges from 26 to 30‰ and water temperature can vary from less than 1°C to more than 23°C (Nixon 1983). NUSCO (1975c) reported that salinities near MNPS range from 26 to 30‰ and water temperatures range from less than 0 to 25°C; since 1976, water temperature and salinity values near MNPS have continued in these ranges (Fig. 2). Thermal and salinity

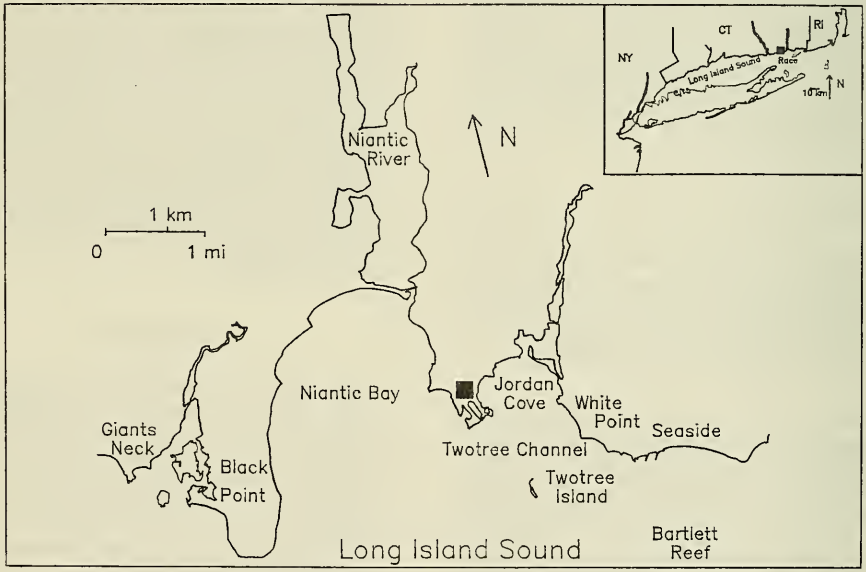

Fig. 1. The area where biological monitoring studies are conducted to assess the effects of the operation of MNPS.

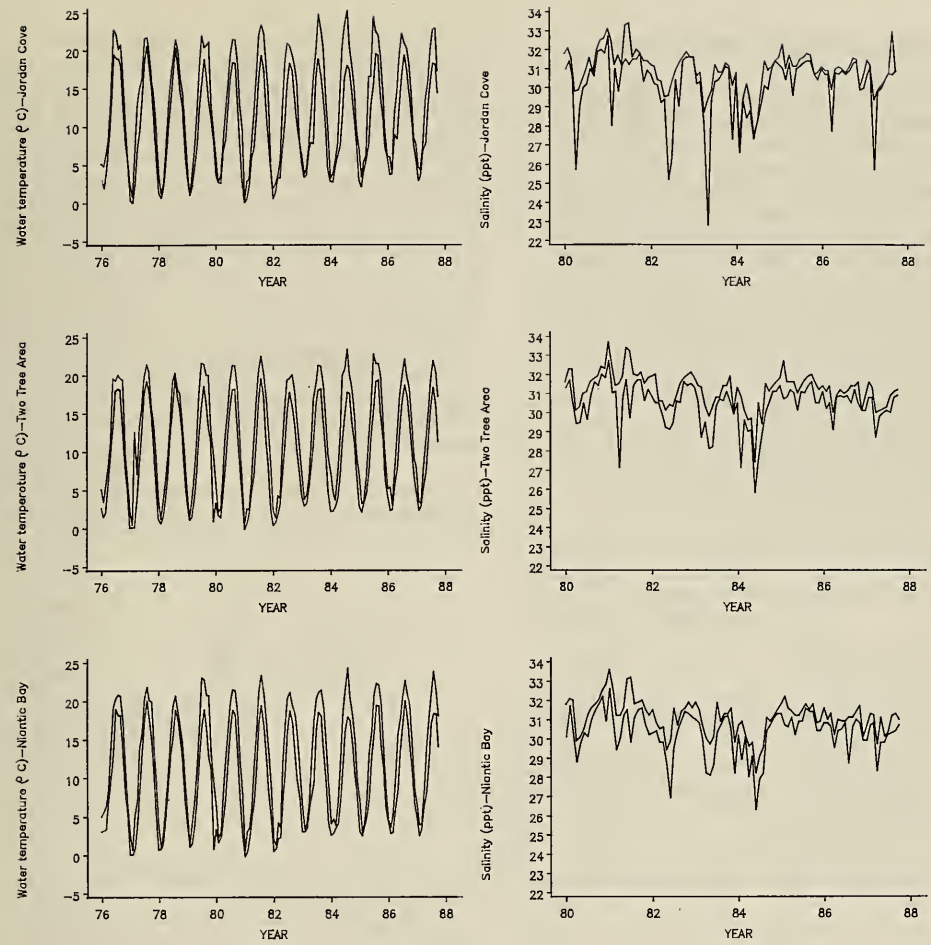

Fig. 2. Water temperature and salinity histories from three areas near MNPS. The sources of these histories are as follows: the Niantic Bay series contains a monthly minimum and maximum water temperature based on measurements taken during ichthyoplankton, trawl, and lobster sampling in the Niantic Bay, including the intake area; the Jordan Cove series contains a monthly minimum and maximum based on measurements taken during trawl and lobster sampling in Jordan Cove; the offshore series contains a monthly minimum and maximum selected from all temperatures measured during trawl and lobster sampling in the Twotree Island and Bartlett Reef areas.

induced stratification occurs in regions unaffected by the strong tidal currents and considerable natural temperature variation is observed in near shore areas (Stoltzenbach and Adams 1979).

Millstone Nuclear Power Station

The MNPS complex consists of three nuclear power plants (Fig. 3). Unit 1, a 660-MWe boiling water reactor, first generated electricity on October 26, 1970 and began commercial operation November 29, 1970. Unit 2, an 870-MWe pressurized water reactor, first generated electricity on November 7, 1975 and began commercial operation in December 1975. Unit 3, a 1150-MWe pressurized water reactor, first generated electricity on February 12, 1986, and began commercial operation April 23, 1986. All three units use once-through condenser cooling water systems. The rated circulating flows for Units 1, 2 and 3 are 26.5, 34.6 and 56.6 m^3/s, respectively. Cooling water is drawn from depths greater than 1m below mean sea level by separate shoreline intakes located on Niantic Bay (Fig. 3). The intake structures, typical of shoreline installations, have coarse bar racks and traveling screens. The cooling water from Units 1, 2, and 3 (nominally heated to a maximum of 13.9, 12.7 and 9.5°C above ambient, respectively) flows from discharge structures and combines in an abandoned granite quarry. The warmed water (about 11°C warmer than ambient when all three units are operating near maximum capacity) exits the quarry at high velocity through two quarry cuts equipped with fish barriers. Once in LIS the effluent mixes with ambient water so that the surface water temperature of the plume has cooled to 4°C above ambient within about 1,100 m of the cuts; the configuration and extent of the thermal plume is highly dynamic and varies with tidal currents (see Hydrothermal Studies section of this report). An operational history including cooling water flow and discharge temperature is provided in Figure 4.

Because the Millstone site has been under development since the early 1960's, a chronology of

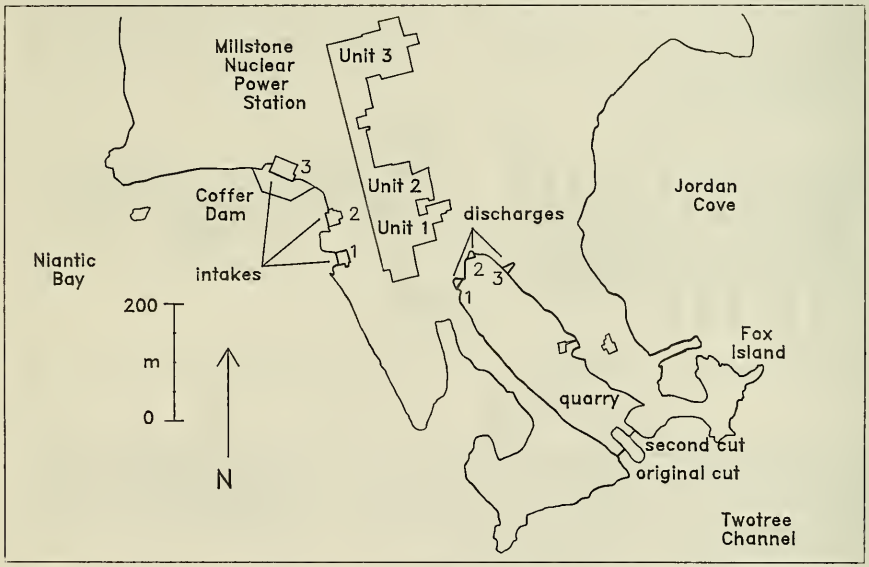

Fig. 3. The MNPS site. Construction of the coffer dam around the Unit 3 intake structure was completed during March 1976. Its removal began during April 1983 and was completed during September 1983. The second cut was opened in August 1983.

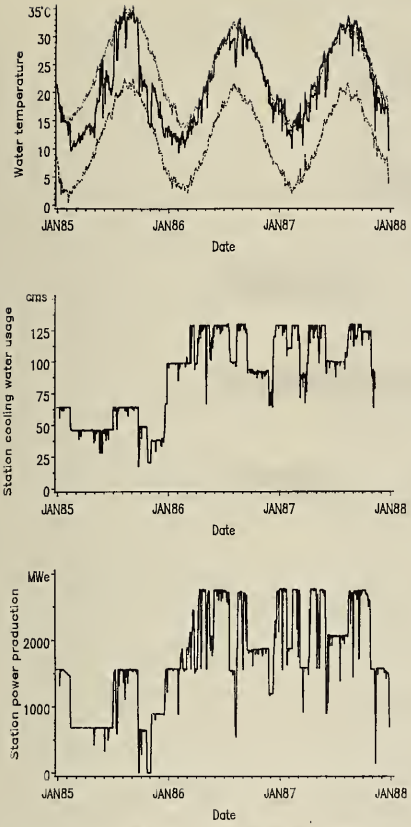

Fig. 4. Station operating conditions January 1985 through December 1987. On the top graph, the lower dashed line is average (Units 1 and 2) intake temperature; upper dashed line is the design effluent temperature; the solid line is the actual effluent temperature (average of measurements made at both quarry cuts). Station cooling water usage (m^3/s, "cms") is plotted on the middle graph and station power production (MWe) is plotted on the bottom graph.

construction and operation events with possible ecological impact implications has been prepared as a reference (Table 1, Fig. 5). Briefly, some of the more important events include construction and removal of cofferdams around the intakes, dredging activities, construction of each of the cuts from the quarry into LIS, initial operation of each unit, and the installation of mitigative devices including the fish barriers at the quarry cuts, and fish return sluiceways at Units 1 and 3 intakes. Demonstrable effects were noted in conjunction with several of these events, most notably construction of the second quarry cut which changed near-field thermal plume dispersal patterns such that higher water temperatures were experienced by the adjacent rocky shore community. In addition, removal of the Unit 3 cofferdam changed sediment characteristics and corresponding infaunal assemblages in the intake area. Simultaneous operation of three units for the first time also increased the volume of cooling water discharged and resulted in sediment scouring immediately downstream of the quarry cuts. These changes and the corresponding ecological effects are discussed further in this report.

A separate report section is included for each continuing monitoring program: rocky intertidal communities, benthic infaunal communities, lobster population dynamics, woodborers, finfish assemblages and winter flounder population dynamics. In addition, two special sections are included, one discussing the theory and application of means calculated from a delta distribution and the other containing a summary of the results of hydrothermal studies done in 1987 during three-unit operation.

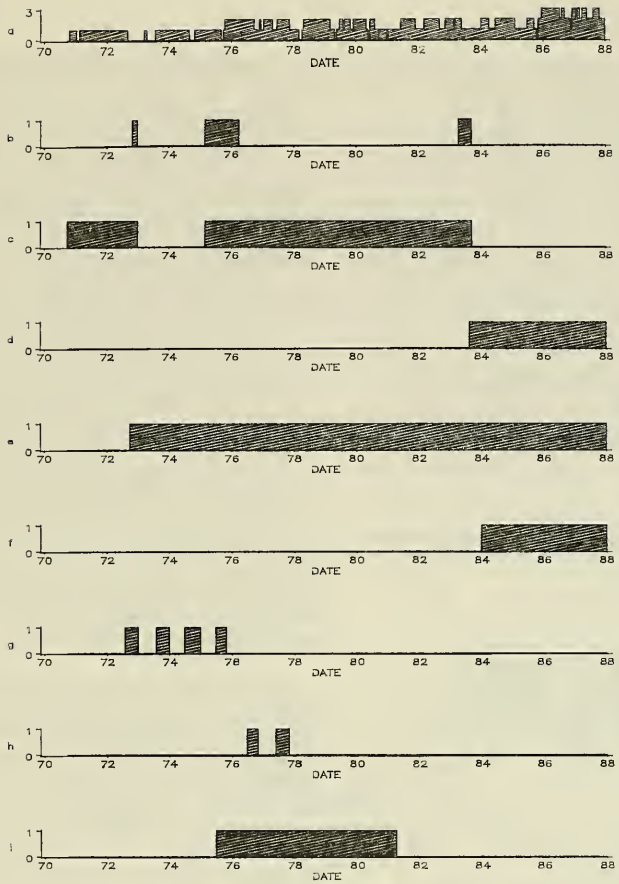

Fig. 5. Major construction and operation events at MNPS lasting longer than 2 weeks: a) number of units operating; b) periods of coffer dam construction and removal; c) presence of coffer dams at Unit 2, then Unit 3 intakes; d) second quarry cut open; e) presence of fish barriers at quarry cut(s); f) presence of fish return system at Unit 1 intake; g) periods when a surface boom was present at Unit 1 intake; h) periods when a surface boom was present at Unit 2 intake; i) period when a bottom boom was present at Unit 1 intake.

TABLE 1. Choronology of major construction and operation events at the Millstone Nuclear Pnwer Station.

Date	Activity	Reference
December 1965	Construction for MNPS 1 began	NUCSO
November 1969	Construction for MNPS 2 began	NUSCO[a] 1973a
October 26, 1970	MNPS 1 initial criticality; produced first thermal effluent	DNGL
November 29, 1970	MNPS 1 initial phase to grid	DNGL
December 28, 1970	MNPS 1 began commercial operation	DNGL
January 15, 1971 - February 22, 1971	MNPS 1 shutdown	DNGL
August - December 1972	Surface boom at MNPS 1	NUSCO 1978a
November 1972	Fish barrier installed at quarry cut	
September 3, 1972 - March 20, 1973	MNPS 1 shutdown	DNGL
November 1972	MNPS 2 coffer dam removed	NUSCO 1973a
April 18 to July 28, 1973	MNPS 1 shutdown	DNGL
August - December 1973	Surface boom at MNPS 1	NUSCO 1978a
July - December 1974	Surface boom at MNPS 1	NUSCO 1978a
September 1 to November 5, 1974	MNPS 1 shutdown	DNGL
July - October 1975	Surface boom at MNPS 1	NUSCO 1978a
July 1975	Bottom boom installed at MNPS 1	NUSCO 1978a
August, 5 1975	MNPS 3 coffer dam construction began	
September 10 to October 20, 1975	MNPS 1 shutdnwn	DNGL[b]
October 7, 1975	MNPS 2 produced first effluent	EDAN
November 7, 1975	MNPS 2 initial criticality; produced first thermal effluent	EDAN
November 13, 1975	MNPS 2 initial phase to grid	DNGL
December 1975	MNPS 2 began commercial operation	NUSCO 1986b
March, 19 1976	MNPS 3 coffer dam construction finished	
June - October 1976	Surface boom at MNPS 2	NUSCO 1978a
October 1 to December 2, 1976	MNPS 1 shutdown	DNGL
December 20, 1976 to January 20, 1977	MNPS 2 shutdown	DNGL
May 6 to June 25, 1977	MNPS 2 shutdown	DNGL
June - October 1977	Surface boom at MNPS 2	NUSCO 1978a
November 20, 1977 to May 1, 1978	MNPS 2 shutdown	DNGL
March 10 to April 15, 1978	MNPS 1 shutdown	DNGL
March 10 to May 21, 1979	MNPS 2 shutdown	DNGL
April 28 to June 27, 1979	MNPS 1 shutdown	DNGL
August 10 to 25, 1979	MNPS 2 shutdown	DNGL
November 1 to December 5, 1979	MNPS 2 shutdown	DNGL
May 7 to June 19, 1980	MNPS 2 shutdown	DNGL
June 1 to June 18, 1980	MNPS 1 shutdown	DNGL
August 15 to October 19, 1980	MNPS 2 shutdown	DNGL
October 3, 1980 to June 16, 1981	MNPS 1 shutdnwn	DNGL
January 2 to 19, 1981	MNPS 2 shutdown	DNGL
December 5, 1981 to March 15, 1982	MNPS 2 shutdown	DNGL[c]
March 1981	Bottom boom removed at MNPS 1	NUEL
September 10 to November 18, 1982	MNPS 1 shutdown	DNGL
March 2 to 18, 1983	MNPS 2 shutdown	DNGL
April - September 1983	MNPS 3 coffer dam removed, intake maintenance dredging	NUEL
May 28, 1983 to January 12, 1984	MNPS 2 shutdown	DNGL
December 1983	Fish return system installed at MNPS 1 intake	NUSCO 1986b
August 1983	Second quarry cut opened	NUSCO 1986a
April 13 to June 29, 1984	MNPS 1 shutdown	DNGL
February 15 to July 4, 1985	MNPS 2 shutdown	DNGL
June 1985	Intake maintenance dredging	NUEL
September 28 to November 7, 1985	MNPS 2 shutdown	DNGL
October 25 to December 22, 1985	MNPS 1 shutdown	DNGL
November 1985	MNPS 3 produced first effluent	EDAN
February 12, 1986	MNPS 3 produced first thermal effluent	EDAN
April 23, 1986	MNPS 3 began commercial operation	
July 25 to August 17, 1986	MNPS 3 shutdown	DNGL
September 20 to December 18, 1986	MNPS 2 shutdown	DNGL
December 1 to 15, 1986	MNPS 1 shutdown	DNGL
January 30 to February 16, 1987	MNPS 2 shutdown	DNGL
March 14 to April 10, 1987	MNPS 3 shutdown	DNGL
June 5 to August 17, 1987	MNPS 1 shutdown	DNGL
November 1, 1987	MNPS 3 shutdown began	DNGL

[a]
[b] DNGL is the daily net generation (MWe) log
[c] EDAN is the environmental data aquisition network
NUEL is the NU Environmental Lab records

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Rocky Intertidal Studies

Introduction

Rocky shores, and the communities which develop upon them, are important components of the marine ecosystem. The intertidal community is among the most productive of the world (Mann 1973). The plants and animals provide food directly and indirectly to fish, birds, invertebrates, even man (Edwards et al. 1982; Menge 1982); they are involved in complex patterns of energy and nutrient transfer (Paine 1966, 1980).

Rocky intertidal communities are particularly suitable for environmental impact assessments. The shores are biologically productive but physically stable; the same area, in many cases the same individual plants and animals, may be sampled over time. Perennial algae and sessile invertebrates integrate the effects of long-term exposure to potential impacts, while motile species and ephemeral algae respond to quickly changing conditions. These characteristics have led to the use of intertidal communities throughout the world for assessment of impacts associated with, e.g., oil spills (Southward and Southward 1978), sewage (Murray and Littler 1978), and thermal pollution (Vadas et al. 1976). Specifically, ecological monitoring programs at every ocean-sited nuclear power plant in New England have included rocky shore studies (MYAPCO 1978; Wilce et al. 1978; NAI 1984).

Rocky shores in the vicinity of MNPS have been subjected to potential impacts resulting from construction and operation of the power station since 1965. To assess these impacts, the Rocky Intertidal Studies were designed and implemented with the following objectives:

1. to identify the attached plant and animal species found on nearby rocky shores,
2. to identify and quantify temporal and spatial patterns of occurrence and abundance of these species, and
3. to identify the physical and biological factors that induce variability in local rocky intertidal communities.

To achieve these objectives, the rocky intertidal studies include qualitative algal collections, abundance measurements of intertidal organisms (percentage of substratum coverage), measurement of rates and patterns of recolonization following small-scale perturbation, and growth studies of *Ascophyllum nodosum*. This report will discuss results of studies performed during the Unit 3 operational period to date (March 1986-September 1987), and compare them to data collected from March 1979 to February 1986 (i.e., the pre-operational period, "pre-op") and summarized in NUSCO (1987). We will assess whether differences exist among communities near MNPS and those removed from potential impact, and whether the magnitude of those differences has changed since 3-unit operations began.

Materials and Methods

Qualitative Collections

The benthic algal flora at nine rocky intertidal stations (Fig. 1) was monitored qualitatively on a monthly basis. These stations are, in order of most to least exposed: Bay Point (BP), Fox Island-Exposed (FE), Millstone Point (MP), Twotree Island (TT), White Point (WP), Seaside Exposed (SE), Seaside Sheltered (SS), Giants Neck (GN), and Fox Island-Sheltered (FS).

Qualitative collections were made over an area sufficiently wide to characterize the flora at each site. Samples were identified fresh or after short-

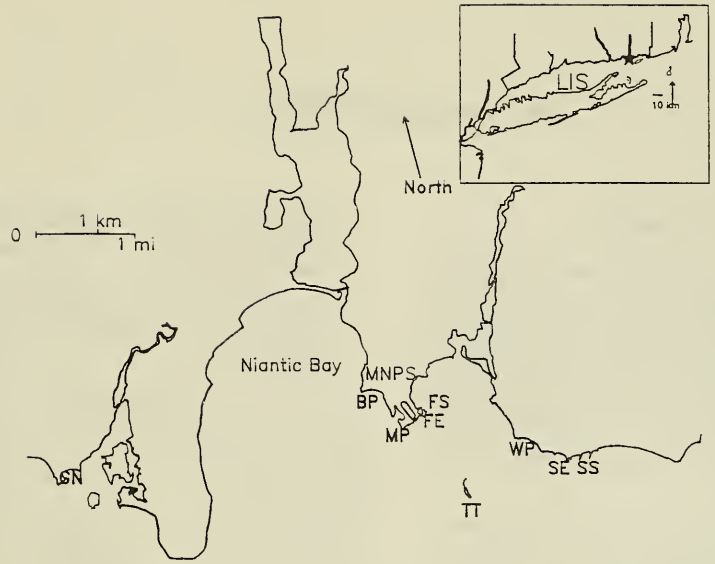

Fig. 1. Location of rocky intertidal sampling sites. GN = Giants Neck, BP = Bay Point, MP = Millstone Point, FE = Fox Island-Exposed, FS = Fox Island-Sheltered, TT = Twotree Island, WP = White Point, SE = Seaside Exposed, SS = Seaside Sheltered.

term freezing. Voucher specimens were preserved using various methods, depending on the material: in 4% formalin/seawater, as dried herbarium mounts, or on microscope slides.

Undisturbed Transects

At each qualitative collection station except TT (because of insufficient exposed bedrock), five permanent transects were established perpendicular to the water-line, one-half meter wide and extending from Mean High Water to Mean Low Water levels. Each transect, composed of 0.5 m x 0.5 m quadrats, was non-destructively sampled six times per year, in odd numbered months (or a total of ten times in the Unit 3 operational period to date). The percentage of substratum cover of all organisms and remaining free space in each quadrat was subjectively determined and recorded. Understory organisms, or species that were partially or totally obscured by the canopy layer, were assigned a percentage that reflected their true abundance.

Recolonization Studies

Transects

Rates and patterns of recolonization following substratum denudation were determined in recolonization transect experiments at four stations: FE, FS, WP, GN. Sample design included two pairs of stations with similar degrees of exposure: exposed at FE and WP, and sheltered at GN and FS. The Fox Island stations, because of their proximity to the MNPS discharge, were considered potentially impacted, while WP and GN were identified as reference stations. Three vertical transects were established at each station; each transect was scraped free of attached algae and invertebrates and burned with a liquid petro-

leum gas torch. All recolonization transects were sampled monthly in the same manner as described for undisturbed transects. In the pre-op period, denudings were performed in April 1979, and again in September 1981 at the same transects, to determine the effect that seasonality of denuding would have on recolonization. Autumn denudings (September 1986) were re-established in the Unit 3 operational period, to assess possible 3-unit effects on recolonization.

Exclusion cages

To investigate the effects of grazing and predation on recolonization rates and patterns, nine areas were selected at each of the recolonization stations, three areas in each of three tide zones. In each area, two 20 cm x 20 cm patches were cleared and burned; one was covered with a stainless steel mesh cage (20 cm x 20 cm x 5 cm, 3 mm mesh), the second left as a control. Each month the percent cover of colonizing organisms was determined. The effect that season of denuding had on rates and patterns of recolonization was also determined. The pre-op series of exclusion cage experiments began in April 1979, June 1980, September 1981, and December 1982; each area was re-burned 15 months after the previous denuding. The exclusion cage studies were re-established in December 1987 to determine the effects of grazing and predation on recolonization under 3-unit operating conditions. Results from these studies will be presented in future annual reports.

Ascophyllum nodosum Studies

Growth and mortality of populations of the perennial brown alga, *Ascophyllum nodosum*, were studied at two control stations (GN, 5.5 km west of the discharge and WP, 1.5 km east of the discharge, Fig. 1) and an experimental station (FL, ca. 75 m east of the original Millstone quarry cut, Fig. 2) from 1979-1984. *Ascophyllum* was eliminated from FL in summer 1984, its loss attributed to elevated water temperatures resulting from the thermal plume of two operating units discharging through two quarry cuts (NUSCO 1985). In spring 1985 a second experimental *Ascophyllum* station (FN) was established between FE and FS (Fig. 2, ca. 250 m from the quarry discharges, northeast of the Fox Island-Exposed sampling site). Following the loss of plants from FL, FN supported the *Ascophyllum* population nearest the discharges.

Ascophyllum plants were measured at monthly intervals from April, after the onset of new vesicle formation, until the following April. Fifty plants at each station were marked with a numbered plastic tag at the base of each plant, and five apices were marked on each plant with colored cable ties. Linear growth was determined by measurements made from the top of the most recently formed vesicle to the apex of the developing axis, or apices if branching had occurred. Vesicles were not large enough to be tagged in April or May, so five tips were measured on each of 50 randomly chosen *Ascophyllum* plants, and monthly measurements of tagged plants began in June. Lost tags were not replaced, and the pattern of loss was used as a measure of mortality. Loss of the entire plant was assumed when the base tag and tip tags were missing. Tip survival was determined in terms of remaining tip tags.

Temperature

Water temperatures were obtained from the EDAN (Environmental Data Acquisition Network) system which continually records a variety of environmental parameters and reports at 15-minute intervals. Ambient water temperatures were recorded by sensors in Unit 1 and 2 intake bays, and effluent water temperatures by sensors in the quarry cuts. Temperatures at FE, MP, and the experimental *Ascophyllum* stations (FL and FN) were measured over several tidal cycles with a portable thermistor and strip chart recorder. During 1987, solid-state data loggers were deployed at several sites in the Millstone area to record water temperatures under differing power plant operating levels; these data were incorporated into models of regimes to which rocky intertidal stations in the vicinity of the MNPS discharge were exposed.

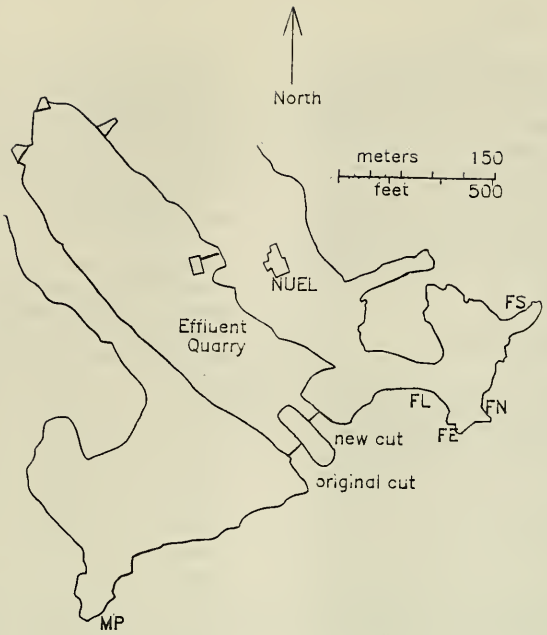

Fig. 2. Detail map of MNPS vicinity. FL = original experimental *Ascophyllum* site (1979-1984), FN = new experimental *Ascophyllum* site (1985-present).

Data Analysis

Relative abundance of intertidal organisms was estimated on the basis of percentage of substratum covered by each taxon. Unoccupied substrata were classed as free space. Similarity between communities was determined by a standardized percentage form of the Bray-Curtis coefficient (Sanders 1960), calculated as:

$$S_{jk} = \sum_{i=1}^{n} \min(P_{ij}, P_{ik})$$

where P(ij) is the percentage of species (i) at station (j), P(ik) is the percentage at station (k), and (n) is the number of species in common. A flexible-sorting, clustering algorithm was applied to the resulting similarity matrix. The calculations were performed on untransformed percentages.

Comparisons of pre-op and 3-unit operational abundances were based on the δ-mean as an index of abundance. This method utilizes the assumption that the non-zero values of percentage cover are log-normally distributed; a complete description of the δ-distribution and rationale for its application is included in the Delta Distribution section of this report.

A Gompertz growth curve was fitted to *Ascophyllum* length data using non-linear regression methods (PROC NLIN, SAS Institute Inc. 1985). The growth curve parameters were compared among years and stations using 2-sample t-tests ($\alpha = 0.05$). *Ascophyllum* mortality data are presented as number of surviving base tags (plants) and tip tags (apices); Unit 3 operational data (1986-87) are plotted against the mean and range of pre-op data (1979-1986). Because of the total elimination of *Ascophyllum* from the original Fox Island *Ascophyllum* station in 1984 and establishment of a new study site, pre-op data from Fox Island excludes the 1984-85 season, and separates 1985-86 (FN) from 1979-84 (FL).

Results and Discussion

Temperature

Since Unit 3 began operation, ambient water temperatures (measured at the MNPS cooling water intakes) have ranged from 2.0 °C (16 February 1987) to 22.1 °C (17 and 18 August 1987). These values are typical of those reported in past years, when minima generally occurred in January-February (1-3 °C) and maxima in August-September (20-22 °C). These temperatures were recorded at a depth of about 3 m below Mean Low Water; insolation of shallow water near the rocky intertidal sampling stations raised summer maxima 2-3 °C, and in winter, slush/ice formed in near-shore shallows.

Effluent water temperatures, measured at the discharge quarry cuts, were dependent on reactor power level and cooling water flow (see Introduction to this report). The designed temperature rise above ambient ΔT was 12 °C for 3-unit, full power operation, but ΔT was less when a unit was shut down and its unheated effluent diluted the discharge of the operating units.

The hydrodynamics of the 3-unit thermal plume, and its behavior at various tidal stages, are described more fully in the Hydrothermal Studies section of this report. Briefly, the 3-unit plume extends into Twotree Island Channel, where it is subject to tidal flushing. This is different from the 2-unit/2-cut plume, that produced elevated water temperatures along the shore between the cuts and the southwest tip of Fox Island, regardless of tidal stage. The effects of the 2-unit effluent were summarized in NUSCO (1987).

The exposure of local rocky shores to the full power 3-unit plume, therefore, varies with tidal stage, as well as distance from the discharges. On an ebbing tide, as water moves out of Long Island Sound, the plume is deflected to the east, across Fox Island. At the original experimental *Ascophyllum* station (FL, Fig. 2), ca. 75 m east of the discharges, the plume elevated water temperature 7-9 °C; temperatures remained elevated for 10-11 hours per tidal cycle. However, temperatures dropped close to ambient levels for 1-2 hours during maximum tidal flooding, as the plume was deflected to the west, and the heated water was displaced.

At FE, ca. 100 m from the discharges, water temperatures were elevated for 9-10 hours per tidal cycle and peaked at 6-8 °C above ambient; ambient water temperatures occurred for 2-3 hours, around the time of high tide. At the new experimental *Ascophyllum* station (FN, Fig. 2), 250 m from the discharges around the tip of Fox Island, maximum water temperature elevation was 4-5 °C above ambient, only during the ebbing tidal stage.

Maximum flood tide deflected the full power, 3-unit plume to the west. At high tide, water temperatures 4 °C above ambient were recorded at MP, ca. 250 m west of the discharges. At this station, there was also a 2-3 °C increase above ambient at the time of low slack water, as the plume spread laterally (cf. Hydrothermal Studies).

The plume characteristics described above are representative of full power, full cooling water flow; because of scheduled and unscheduled shutdowns, these conditions existed for less than 50% of the Unit 3 operational period to date. Specifically, we have not seen consistent full power

operation during periods of maximum ambient water temperature. Various combinations of operating units, varying water flow, and changing meteorological conditions affect the behavior of the thermal plume, and the degree to which the plume affects intertidal communities. The generalized temperature regimes provide a physical framework for interpreting the biological responses of rocky intertidal plants and animals discussed in the following sections.

Qualitative Studies

NUEL qualitative studies were designed to identify algal species present in intertidal and shallow subtidal areas in the vicinity of MNPS throughout the year, and to characterize their spatial and temporal distribution patterns. Changes in these patterns, i.e. differences in species composition among stations or years, may indicate environmental changes and require assessment of whether the changes were related to construction or operation of MNPS. Floristic analyses have been used in similar environmental impact assessments, e.g., Wilce et al. (1978) and NAI (1984).

A rich and diverse flora occupies the rocky intertidal monitoring area, relative to other areas of Long Island Sound. Overall, 128 species (excluding blue-greens and diatoms) have been identified in the Unit 3 operational period, but not all species were found at any one station, nor were they found in any one collection period. Qualitative algal collections for the 3-unit monitoring period are presented as number of stations at which each species was found in any given month, and as number of months each species was found at any given station (Table 1).

Fucus vesiculosus is the only alga that was collected in every month at every station during 3-unit operation, although *Chondrus crispus* and *Ascophyllum nodosum* were ubiquitous at all sites except Fox Island-Exposed (dissimilarities between the flora at FE and those at other stations will be discussed in a later section). Other species (e.g., *Ceramium rubrum*, *Ulva lactuca*, *Codium fragile*), while not ubiquitous, were common throughout the area, throughout the sampling period.

Of the 128 benthic algal species found in the 3-unit period, several were site-specific (Table 1), such as *Laminaria digitata* at TT, *Fucus spiralis* at BP, and *Agardhiella subulata* at FE. In addition, some species were characteristically rare at a particular station, such as *Corallina officinalis* at GN. The local flora also showed seasonal trends. Some examples of temporal differences include *Bangia atropurpurea*, *Dumontia contorta*, and *Monostroma* spp. as most common in winter-spring, *Leathesia difformis*, *Petalonia fascia*, and *Scytosiphon lomentaria* in spring-summer, *Champia parvula* and *Giffordia mitchelliae* in summer-autumn, and *Spermothamnion repens* and *Sphacelaria cirrosa* in autumn-winter (Table 1). Spring collections were typically richest and winter collections were poorest. These patterns were noted in the pre-op flora as well (NUSCO 1987).

Some local species exhibit no apparent spatial or temporal pattern of occurrence, i.e., they are not characteristic of a particular station or season but occur sporadically among sampling sites. Sporadic occurrence of many algal species accounts for the fact that algae collected in any one year will comprise only a portion of the total flora, represented by aggregated collections since 1979. The presence of infrequent or occasional species also explains why new species are added to the overall species list each year. For example, *Antithamnionella floccosum* and *Nemalion helminthoides* were newly recorded in the Unit 3 period. *Antithamnionella* was found throughout the period at 6 out of 9 stations (generally at exposed sites) and *Nemalion* only once, in July at BP. Conversely, some rare and small epiphytic algal species that had been reported between March 1979 (when this sampling program began) and February 1986 (the last sampling month of the pre-op period) have not yet been found in the 3-unit operational period.

TABLE 1. Number of times each species was collected, by month and station, March 1986-September 1987.

Chlorophyta	1986 M	A	M	J	J	A	S	O	N	D	1987 J	F	M	A	M	J	J	A	S	GN	BP	MP	TT	FE	FS	WP	SE	SS	Times found
Ulothrix flacca	6	7	1	2	2	0	0	1	0	2	6	4	7	5	1	1	1	0	0	7	2	6	5	4	4	5	8	5	46
Urospora penicilliformis	6	4	1	2	2	2	2	1	2	4	6	5	6	5	3	3	3	1	2	9	5	6	6	8	10	7	4	5	60
Urospora wormskjoldii	0	0	2	0	0	0	0	1	0	1	0	2	2	1	2	0	3	3	1	2	0	2	2	3	3	4	1	1	18
'Urospora collabens'	1	0	1	0	0	0	0	0	0	0	1	1	0	0	1	0	1	0	0	0	3	0	0	2	0	1	0	0	6
Entocladia viridis	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	1	0	0	3
Monostroma grevillei	6	7	4	0	0	0	0	0	0	0	0	1	5	6	3	0	0	0	0	3	5	4	6	1	4	1	5	3	32
Monostroma pulchrum	8	8	6	0	0	0	0	0	0	0	0	0	6	9	6	0	0	0	0	4	4	5	6	1	6	5	6	6	43
Spongomorpha arcta	3	2	5	2	1	0	0	0	0	0	0	1	0	0	3	1	0	0	0	1	1	5	4	1	2	3	1	0	18
Spongomorpha aeruginosa	1	3	6	1	0	0	0	0	0	0	0	0	0	2	1	1	0	0	0	2	4	3	0	1	1	2	1	1	15
Blidingia minima	6	5	6	5	4	6	4	8	3	2	5	5	3	6	3	7	5	7	6	10	4	16	16	12	1	13	10	14	96
Enteromorpha clathrata	0	0	2	0	2	4	6	2	2	1	1	0	0	2	2	2	4	7	3	8	4	3	0	7	6	7	0	5	40
Enteromorpha flexuosa	4	2	7	3	4	2	7	5	7	3	2	2	5	6	3	4	4	3	4	12	9	9	4	15	2	13	5	8	77
Enteromorpha groenlandica	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	2	0	0	0	2
Enteromorpha intestinalis	4	6	2	5	5	5	4	3	4	5	5	4	2	2	4	1	4	3	4	9	8	11	6	8	3	13	6	8	72
Enteromorpha linza	5	6	7	7	5	5	5	7	0	0	1	1	4	7	5	6	4	1	5	11	13	12	7	11	6	12	6	3	81
Enteromorpha prolifera	1	3	0	2	2	5	0	2	1	1	3	3	1	3	2	0	2	1	1	6	3	4	3	2	2	4	3	6	33
Enteromorpha torta	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	1	0	0	2
Enteromorpha ralfsii	0	0	0	2	0	1	0	0	0	0	0	1	0	0	0	1	3	1	0	3	0	1	2	0	2	1	0	0	9
Percursaria percursa	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	2
Ulva lactuca	8	6	8	9	9	9	9	9	9	9	8	9	8	8	8	9	9	9	9	19	18	18	18	16	18	18	19	18	162
Prasiola stipitata	0	1	2	2	2	1	1	2	0	1	2	1	2	2	1	2	2	1	1	3	0	0	14	0	0	1	7	1	26
Chaetomorpha linum	4	2	5	8	8	9	7	8	6	7	6	7	1	4	6	8	9	7	7	14	16	14	16	3	13	13	15	15	119
Chaetomorpha aerea	3	2	2	3	2	4	4	5	2	4	2	2	2	4	3	1	3	4	0	5	3	8	1	9	10	10	2	4	52
Cladophora albida	0	1	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	1	0	1	0	0	3
Cladophora flexuosa	1	0	4	6	7	3	5	4	3	2	1	0	0	1	5	7	7	4	4	6	11	5	5	8	10	8	4	7	64
Cladophora refracta	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	2	1	2	0	0	1	3	1	2	1	0	1	0	9
Cladophora sericea	1	2	0	2	1	3	3	2	2	2	2	0	1	4	4	2	4	3	3	11	1	3	1	4	9	8	1	3	41
Cladophora hutchinsiae	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1
Cladophora rupestris	0	0	1	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	2	4
Cladophora ruchingeri	0	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	3
Rhizoclonium riparium	1	2	2	3	3	3	3	3	1	3	2	0	1	1	1	4	4	3	2	11	1	0	2	2	12	12	0	2	42
'Rhizoclonium kerneri'	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	1	1	0	2
Bryopsis plumosa	0	0	0	0	3	0	1	0	0	1	1	1	0	0	0	3	2	0	1	2	0	2	4	1	1	0	1	12
Bryopsis hypnoides	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	3	0	0	0	1	0	0	0	0	4
Derbesia marina	0	0	0	0	0	0	0	1	0	1	0	0	0	0	1	0	0	1	0	0	0	0	0	4	0	0	0	0	4
Codium fragile	6	5	4	7	7	9	8	6	5	9	6	8	5	4	5	8	9	8	7	14	12	11	17	19	17	17	7	12	126

Values represent number of stations at which each species was found in any given month (out of 9), and number of months that each species was found at any station (out of 19).
Last column represents the total number of times that each species was found during the report period (out of a possible 171).

TABLE 1. (cont.)

Rhodophyta	1986 M	A	M	J	J	A	S	O	N	D	1987 J	F	M	A	M	J	J	A	S	GN	BP	MP	TT	FE	FS	WP	SE	SS	Times found
Grinnellia americanum	0	0	0	0	0	1	2	1	1	0	0	0	0	0	0	1	0	1		0	0	0	1	2	0	2	0	2	7
Phycodrys rubens	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	1	0	0	1	0	1	3
Dasya baillouviana	0	1	0	0	0	1	1	2	1	1	0	0	0	0	0	0	0	1	0	0	1	0	1	4	0	2	0	0	8
Chondria baileyana	0	0	0	0	0	1	2	1	0	0	0	0	0	0	0	0	0	0	1	3	0	1	1	0	0	0	0	0	5
Polysiphonia denudata	0	0	0	0	1	0	0	0	0	0	1	1	0	0	2	0	0	0	0	0	2	1	1	0	0	0	0	1	5
Polysiphonia harveyi	0	2	0	1	6	6	5	3	1	1	1	1	1	2	2	5	6	3	4	3	3	7	6	11	3	5	4	8	50
Polysiphonia lanosa	7	4	6	8	5	4	6	7	6	5	6	5	5	6	6	5	6	5	6	6	18	19	9	0	10	17	11	18	108
Polysiphonia nigra	1	0	0	0	0	0	0	0	0	0	1	0	0	1	0	1	0	0	0	1	0	0	0	0	0	2	1	0	4
Polysiphonia nigrescens	0	0	0	1	1	2	0	1	1	1	0	3	0	1	1	2	1	2	2	1	3	1	1	1	0	7	1	4	19
Polysiphonia urceolata	0	0	1	3	0	0	0	0	0	0	0	0	2	1	1	0	0	0	0	2	2	1	2	0	0	1	0	0	8
Polysiphonia novae-angliae	7	3	4	9	9	9	9	9	9	9	8	7	3	2	1	5	6	8	9	14	15	16	14	18	12	16	9	12	126

Phaeophyta	1986 M	A	M	J	J	A	S	O	N	D	1987 J	F	M	A	M	J	J	A	S	GN	BP	MP	TT	FE	FS	WP	SE	SS	Times found
Ectocarpus fasciculatus	0	3	5	4	2	2	3	1	3	1	0	0	2	2	2	4	3	1	1	4	9	1	10	0	1	7	3	4	39
Ectocarpus siliculosis	3	4	3	6	2	1	0	0	0	0	1	3	2	3	4	1	2	1	1	6	5	2	4	2	2	9	3	4	37
Ectocarpus sp.	1	0	0	1	1	1	0	0	0	1	0	0	0	1	0	0	0	0	0	2	0	2	1	0	0	0	0	1	6
Giffordia granulosa	0	0	2	1	0	0	0	0	1	0	0	1	0	0	0	1	0	0	1	2	0	0	1	1	1	2	0	0	7
Giffordia mitchelliae	0	0	2	1	1	5	4	7	2	2	2	1	1	0	0	1	2	4	4	8	8	1	4	11	2	5	0	0	39
Pilayella littoralis	3	4	5	2	1	0	0	3	1	1	1	2	2	4	4	3	1	3	0	11	1	0	7	1	12	3	2	3	40
Spongonema tomentosum	6	3	2	0	0	1	0	2	0	2	1	1	4	2	0	0	1	0	0	2	3	3	4	3	1	3	4	2	25
Ralfsia verrucosa	5	6	5	0	4	7	3	8	6	6	3	3	1	2	1	3	4	7	6	16	8	9	7	2	15	14	4	5	80
Elachista fucicola	6	5	6	7	7	6	1	6	8	2	1	4	7	7	3	9	7	3	5	13	13	11	12	5	5	15	14	12	100
Halothrix lumbricalis	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	2
Leathesia difformis	0	2	5	4	5	0	0	0	0	0	0	0	0	1	2	4	2	0	0	5	3	8	1	2	3	3	0	0	25
Chordaria flagelliformis	0	0	2	1	0	0	0	0	0	0	0	0	0	0	1	0	2	2	1	1	6	0	1	0	0	1	0	0	9
Sphaerotrichia divaricata	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1
Asperococcus fistulosus	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1
Desmotrichum undulatum	0	1	0	2	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	2	1	0	0	0	0	4
Phaeosaccion collinsii	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1
Punctaria latifolia	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1
Punctaria plantaginea	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	2
Petalonia fascia	9	9	9	9	5	0	0	2	4	5	6	8	6	8	7	5	4	0	0	10	11	12	15	11	9	12	10	6	96
Scytosiphon lomentaria	9	9	9	9	5	1	0	0	0	0	4	5	8	8	8	8	3	0	0	11	8	13	9	10	10	10	9	6	86
Desmarestia aculeata	1	1	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	1	1	1	0	3	0	0	1	0	1	7
Desmarestia viridis	2	4	4	5	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1	6	0	1	3	2	4	17
Chorda filum	0	1	0	2	3	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	4	0	0	0	1	2	8
Chorda tomentosa	1	1	4	1	0	0	0	0	0	0	0	0	1	1	2	0	0	0	0	0	2	0	6	0	0	0	2	1	11
Laminaria digitata	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1
Laminaria longicruris	2	1	1	2	1	0	1	1	0	1	1	1	1	3	0	1	0	1	1	0	0	0	12	0	0	3	2	2	19
Laminaria saccharina	3	4	6	7	7	7	4	5	5	3	3	3	5	3	8	9	6	8	4	10	12	14	16	5	7	16	12	8	100
Sphacelaria cirrosa	2	1	1	2	0	0	3	1	2	4	2	0	1	0	1	0	1	1	4	5	0	0	0	6	8	3	2	2	26
Ascophyllum nodosum	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	19	19	19	19	0	19	19	19	19	152
Fucus distichus s edentatus	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	2	0	0	0	0	0	2
Fucus distichus s evanescens	2	1	0	1	2	1	0	0	0	0	0	0	2	2	0	0	1	0	1	0	2	2	7	0	0	2	0	0	13
Fucus spiralis	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	1	1	0	1	0	5	0	0	0	0	0	0	0	5
Fucus vesiculosus	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	19	19	19	19	19	19	19	19	19	171

TABLE 1. (cont.)

Rhodophyta	1986 M	A	M	J	J	A	S	O	N	D	1987 J	F	M	A	M	J	J	A	S	GN	BP	MP	TT	FE	FS	WP	SE	SS	Times found
Goniotrichum alsidii	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	0	0	2	1	0	0	0	0	0	0	0	3
Erythrotrichia ciliaris	0	1	0	2	1	4	4	5	4	3	1	0	0	0	1	0	0	1	3	7	3	2	0	8	3	4	2	1	30
Erythrotrichia carnea	0	0	0	0	0	0	0	0	2	0	1	0	0	0	0	0	0	1	0	0	2	0	0	0	2	0	0	0	0	4
Erythrocladia subintegra	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1
Erythropeltis discigera	2	1	0	0	1	0	1	2	2	2	1	0	0	0	0	0	0	0	1	0	3	2	2	3	0	2	1	0	13
Bangia atropurpurea	9	6	2	1	1	1	2	4	1	2	6	5	8	6	2	3	1	0	4	8	6	9	7	11	4	10	7	2	64
Porphyra leucosticta	8	8	7	5	0	0	1	4	5	2	7	6	8	9	7	2	1	1	0	7	7	12	9	10	9	10	9	8	81
Porphyra umbilicalis	7	8	7	4	3	2	0	4	2	2	5	5	7	6	6	3	3	3	3	9	5	11	9	11	8	8	13	6	80
Porphyropsis coccinea	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	2
Audouinella secundata	4	4	3	3	4	1	2	3	0	1	4	1	3	3	2	1	1	0	1	6	7	7	3	0	3	4	5	6	41
Audouinella daviesii	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
Audouinella saviana	1	2	1	2	1	0	1	2	3	0	2	1	0	2	0	0	0	0	0	2	2	1	3	4	0	5	0	1	18
Audouinella sp.	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1
Gelidium crinale	1	1	1	1	1	2	1	1	2	2	2	1	1	1	1	1	2	1	2	6	0	0	0	0	19	0	0	0	25
Nemalion helminthoides	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	1
Bonnemaisonia hamifera	1	1	3	3	2	0	0	0	0	0	0	1	0	1	2	3	3	0	0	0	0	0	10	0	0	3	3	4	20
'Trailliella intricata'	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1
Agardhiella subulata	1	1	0	0	1	0	1	1	1	1	1	1	1	0	0	1	0	0	1	0	0	0	0	11	0	0	0	0	11
Polyides rotundus	1	0	0	2	0	1	1	0	0	1	1	0	0	0	1	0	0	0	0	0	0	1	3	0	0	3	0	1	8
Cystoclonium purpureum	7	3	5	6	3	1	1	3	3	2	5	3	2	4	4	2	1	0	1	6	3	10	13	1	2	7	6	8	56
Gracilaria tikvahiae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	1
Ahnfeltia plicata	2	2	4	2	2	1	0	2	1	2	1	4	4	2	2	3	0	0	2	0	3	7	10	0	3	9	3	1	36
Phyllophora pseudoceranoides	1	0	0	1	0	2	1	3	2	5	1	3	0	0	2	1	0	0	1	2	1	2	5	0	0	8	2	3	23
Phyllophora truncata	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	0	0	2	0	0	3
Chondrus crispus	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	9	9	9	19	19	19	19	3	19	19	19	19	155
Gigartina stellata	8	7	4	7	5	7	5	6	6	5	4	6	5	6	6	4	4	4	5	5	7	15	19	0	6	19	17	16	104
Rhodophysema georgii	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	2
Corallina officinalis	5	5	5	7	2	7	5	4	5	6	5	7	4	4	5	6	5	4	5	0	17	18	5	16	19	15	4	2	96
Dumontia contorta	8	7	7	3	0	0	0	0	0	1	4	4	5	6	6	1	0	0	0	7	4	5	9	0	9	5	5	8	52
Choreocolax polysiphoniae	0	0	1	1	0	0	0	0	0	0	1	0	2	0	1	0	0	0	0	0	4	1	0	0	0	0	0	1	6
Hildenbrandia rubra	0	0	0	0	1	0	1	1	0	1	1	0	0	0	0	0	0	0	1	0	0	0	5	0	0	1	0	0	6
Palmaria palmata	1	2	2	1	1	1	1	1	2	1	1	4	1	2	2	1	1	2	1	0	1	0	17	1	0	6	0	3	28
Champia parvula	2	0	0	0	4	8	6	5	6	3	1	1	0	0	0	2	2	7	7	5	3	5	6	7	7	10	5	6	54
Lomentaria baileyana	0	0	0	1	0	0	3	1	0	0	0	0	0	0	0	0	0	2	1	2	0	0	0	1	4	0	0	1	8
Lomentaria clavellosa	0	0	1	0	0	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1	1	0	0	0	0	2	4
Lomentaria orcadensis	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
Antithamnion americanum	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1
Antithamnion cruciatum	4	1	2	2	4	9	8	8	6	5	6	4	0	0	0	4	3	4	4	3	11	11	10	9	9	10	5	6	74
Antithamnion pylaisaei	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	2	0	0	1	0	0	0	1	1	0	1	4
Callithamnion roseum	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	1	1	0	0	1	1	2	0	0	0	0	4
Callithamnion tetragonum	4	2	1	1	0	2	4	4	3	1	1	1	2	1	0	1	0	1	1	0	4	9	6	1	2	6	0	2	30
Callithamnion baileyi	0	2	1	0	1	0	0	2	3	1	1	1	1	1	1	0	0	2	0	0	1	7	3	3	0	0	2	0	0	16
Ceramium deslongchampii v hooperi	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	2
Ceramium diaphanum	0	0	0	0	3	5	5	3	0	0	0	0	0	0	0	0	2	4	1	0	5	0	6	1	0	5	1	5	23
Ceramium rubrum	6	7	5	8	7	8	9	9	7	8	6	8	5	4	8	7	8	7	6	13	19	11	19	9	16	17	13	16	133
Spermothamnion repens	4	1	3	5	4	5	3	7	5	7	4	2	2	1	0	2	2	2	1	9	10	3	4	4	5	13	6	6	60
Spyridia filamentosa	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	1	0	2	1	0	1	0	0	0	0	0	4
Antithamnionella floccosum	0	0	0	0	0	1	1	0	0	1	1	1	2	1	1	1	1	3	4	0	1	9	2	4	0	1	1	0	18

Comparing the flora represented by the 1986 collections to those collected in each of the pre-op years (Table 2), there was a tendency at most stations for red algae to comprise a smaller proportion of the total flora found since Unit 3 began operation than in the pre-op period. In most cases, the relative decrease in the number of red algal species was attributed to the absence (in the 3-unit operational period, to date) of some small, rarely found plants. At all stations except FE, the proportion of reds in 1986 was within one percentage point of previous years' values, and the decrease is not regarded as a major community change. At FE, however, the proportion of red algae in 1986 (35%) was 10 percentage points lower than the pre-op summary, and the number of red algal species (22) was at least 7 less than in any previous year except 1985 (Table 2).

These patterns represent a continuation of spatial and temporal trends that have occurred at FE since the opening of the second quarry cut in August 1983 (NUSCO 1985), and are different from those identified at the other sampling sites. Many perennial species and associated epiphytes at FE were eliminated in the summer of 1984 when water temperatures exceeded 28 °C. Community changes resulting from elevated water temperatures included the loss of established populations of perennial macroalgae such as *Chondrus crispus*, *Ascophyllum nodosum*, and *Fucus vesiculosus*, and increased abundance and persistence of opportunistic species such as the greens *Codium fragile* and *Enteromorpha flexuosa*. Elevated temperatures at FE also caused a decrease in the number of brown algal species, thereby decreasing the proportion of browns relative to reds and greens (cf. Schneider 1981; Quarry Study in NUSCO 1987). Changes at FE were identified both as a decrease in species number (from a total of 80 species in 1982 to 50 in 1985), and as a shift in divisional proportions (more greens, fewer browns and reds).

Local spatial and temporal distribution patterns are also apparent when the qualitative algal collections are presented as number of species in each division (Table 2). Number of species in each division and total number of species at each station during the Unit 3 operational period generally fell within the range of previous years. Fewer species have been collected in the 19 months since Unit 3 began operation than were found in the 7 years of pre-op studies. Continued collection during the 3-unit operational period will augment the 3-unit species list.

Relationships between the pre-op and 3-unit operational floras may also be represented graphically (Fig. 3). When division proportions of the overall flora were analyzed, proportions were similar and independent of species number. Relative species proportions in the first 12 months of the 3-unit operational period (45:26:29) were virtually identical to those of the pre-op summary (Fig. 3). The local flora proportions continue to be similar to those of other researchers in the northwest Atlantic (Vadas 1972; Wilce et al. 1978; Schneider et al. 1979; Mathieson et al. 1981; Mathieson and Hehre 1986).

In brief, the algal flora of the Millstone area, as represented by collections in the 3-unit operational period to date, was similar to that reported for 2-unit operating conditions. The community changes described at Fox Island-Exposed were attributed to elevated water temperatures resulting from opening the second quarry cut, not from start-up of Unit 3. However, most of these changes have persisted during 3-unit operations, as water temperatures close to 28 °C have occurred at FE in summer. The FE community has shown some response to the periodic incursion of ambient-temperature water that occurs near the time of high tide (see Temperature section); e.g., *Fucus* persists throughout the year, and isolated *Chondrus* plants have been collected. However, *Ascophyllum* has not recolonized, and *Codium* and *Enteromorpha* remain the most abundant species at FE. Continued monitoring at FE and at nearby stations (e.g., FS, MP) will allow us to determine whether the observed thermal effects will remain within present bounds.

TABLE 2. Number of species by station, year, and division (percentages are in parentheses). Pre-op (3-79 to 2-85) and 3-unit operational (3-86 to 9-87) summaries are included. Each year represented by collections from March to following February.

Station	Division	1979	1980	1981	1982	1983	1984	1985	pre-op summary	1986	3-unit summary
BP	reds	31(43)	33(47)	47(50)	40(46)	34(43)	39(46)	33(46)	57(44)	33(43)	39(46)
	browns	16(22)	18(26)	24(26)	24(28)	18(22)	21(25)	20(27)	36(27)	21(27)	21(25)
	greens	25(35)	19(27)	23(24)	22(26)	28(35)	25(29)	20(27)	38(29)	23(30)	25(29)
FE	reds	33(43)	33(46)	31(40)	33(41)	29(42)	29(45)	21(42)	50(45)	22(35)	28(39)
	browns	18(24)	16(22)	22(29)	17(21)	17(24)	14(21)	10(20)	26(23)	16(26)	16(22)
	greens	25(33)	23(32)	24(31)	30(38)	24(34)	22(34)	19(38)	36(32)	24(39)	28(39)
FS	reds	32(45)	29(42)	28(39)	39(49)	39(49)	37(45)	28(42)	54(44)	23(38)	23(35)
	browns	16(23)	15(22)	21(29)	16(20)	16(20)	22(27)	15(23)	32(25)	16(27)	17(26)
	greens	23(32)	25(36)	23(32)	25(31)	24(31)	23(28)	23(35)	38(31)	21(35)	25(39)
GN	reds	28(42)	33(45)	37(44)	38(45)	37(45)	36(43)	34(44)	56(45)	27(41)	28(40)
	browns	17(25)	18(24)	23(27)	20(23)	17(21)	20(24)	19(25)	30(24)	17(26)	18(25)
	greens	22(33)	23(31)	25(29)	27(32)	28(34)	28(33)	24(31)	39(31)	22(33)	25(35)
MP	reds	-	-	-	30(40)	33(42)	31(40)	32(44)	51(45)	29(43)	34(47)
	browns	-	-	-	20(27)	22(29)	23(30)	18(24)	30(27)	16(24)	16(22)
	greens	-	-	-	25(33)	22(29)	23(30)	24(32)	32(28)	22(33)	22(31)
SE	reds	26(45)	24(44)	34(48)	33(46)	32(46)	29(41)	28(44)	48(44)	24(41)	25(40)
	browns	15(26)	17(31)	19(27)	20(27)	15(22)	20(29)	15(24)	29(27)	15(25)	16(25)
	greens	17(29)	14(25)	18(25)	20(27)	22(32)	21(30)	20(32)	32(29)	20(34)	22(35)
SS	reds	29(43)	32(48)	39(47)	40(45)	40(47)	43(51)	30(44)	57(46)	29(45)	34(46)
	browns	16(24)	13(19)	23(27)	21(24)	23(27)	19(22)	17(25)	31(25)	17(26)	18(24)
	greens	22(33)	22(33)	22(26)	27(31)	22(26)	23(27)	21(31)	36(29)	19(29)	22(30)
TT	reds	-	-	-	39(45)	37(46)	37(48)	40(51)	54(50)	32(44)	40(45)
	browns	-	-	-	26(30)	23(29)	22(29)	20(26)	28(25)	22(30)	27(30)
	greens	-	-	-	22(25)	20(25)	18(23)	18(23)	27(25)	19(26)	22(25)
WP	reds	32(44)	38(47)	44(46)	42(44)	39(43)	43(48)	41(48)	58(46)	36(44)	39(44)
	browns	18(25)	20(24)	25(26)	24(25)	23(26)	22(24)	23(26)	33(26)	20(25)	20(23)
	greens	22(31)	24(29)	27(28)	29(31)	28(31)	25(28)	23(26)	36(28)	25(31)	29(33)
Total	reds	44(44)	47(46)	60(47)	58(44)	57(46)	61(45)	54(46)	73(46)	54(45)	59(46)
	browns	26(26)	26(25)	35(27)	35(27)	32(25)	34(26)	29(25)	40(25)	31(26)	33(26)
	greens	30(30)	30(29)	34(26)	38(29)	37(29)	38(29)	34(29)	45(29)	35(29)	36(28)

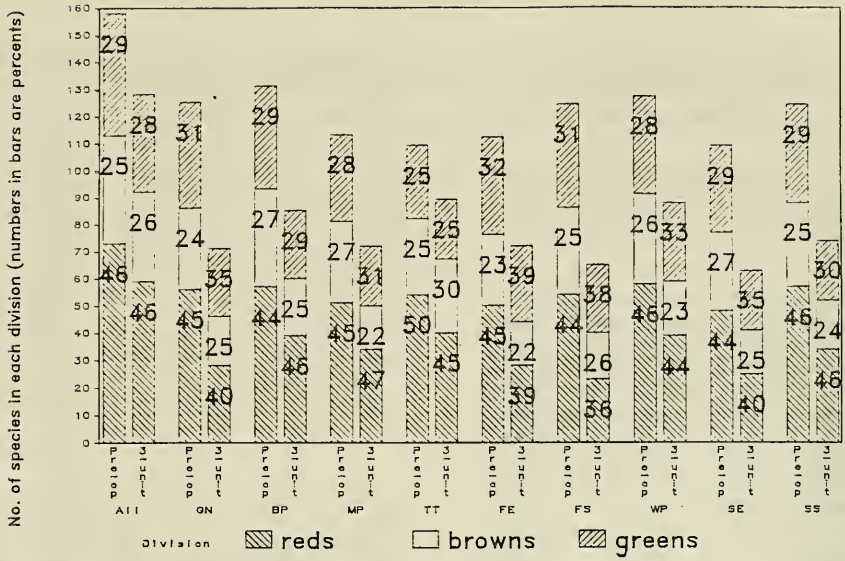

Fig. 3. Relative species proportions of major algal divisions under pre-operational and 3-unit operation (March 1986-February 1987) conditions. Numbers in bars represent percentage of total flora; height of bars represents numbers of species in each division.

Undisturbed Transects

Zonation is a universal feature of rocky intertidal communities (Stephenson and Stephenson 1949, 1972; Lewis 1964). Local rocky intertidal communities are separated into horizontal bands representing the high, mid, and low intertidal zones, where the high intertidal (Zone 1) consists mostly of bare rock and barnacles (*Balanus balanoides*), the mid intertidal (Zone 2) is dominated by a canopy of the perennial brown alga *Fucus vesiculosus* over an understory of barnacles, and the low intertidal (Zone 3) is dominated by the perennial red alga *Chondrus crispus*. Although zonation appears stable on a localized scale, it is subject to natural influences such as degree of exposure, desiccation, temperature, storms, ice-scour, predation, and competition, as well as man-induced influences, which can alter the abundance of intertidal populations and increase the complexity of the community.

Similarity Dendrogram

To discern pattern in this complexity, the Bray-Curtis similarity index has been utilized to characterize the community at each station in terms of average annual abundance of each mid and low intertidal taxon (measured as percentage of coverage on permanently marked, undisturbed transects, sampled six times per year). The similarity index was calculated for each station/year combination, and a clustering algorithm was applied to the resultant similarity matrix. Examination of the hierarchial dendrogram (Fig. 4) allows generation of hypotheses concerning the relationships among stations and among years. First, the general patterns of similarity among stations and years (including 1986 data, marked with asterisks in Fig. 4) were identical to those

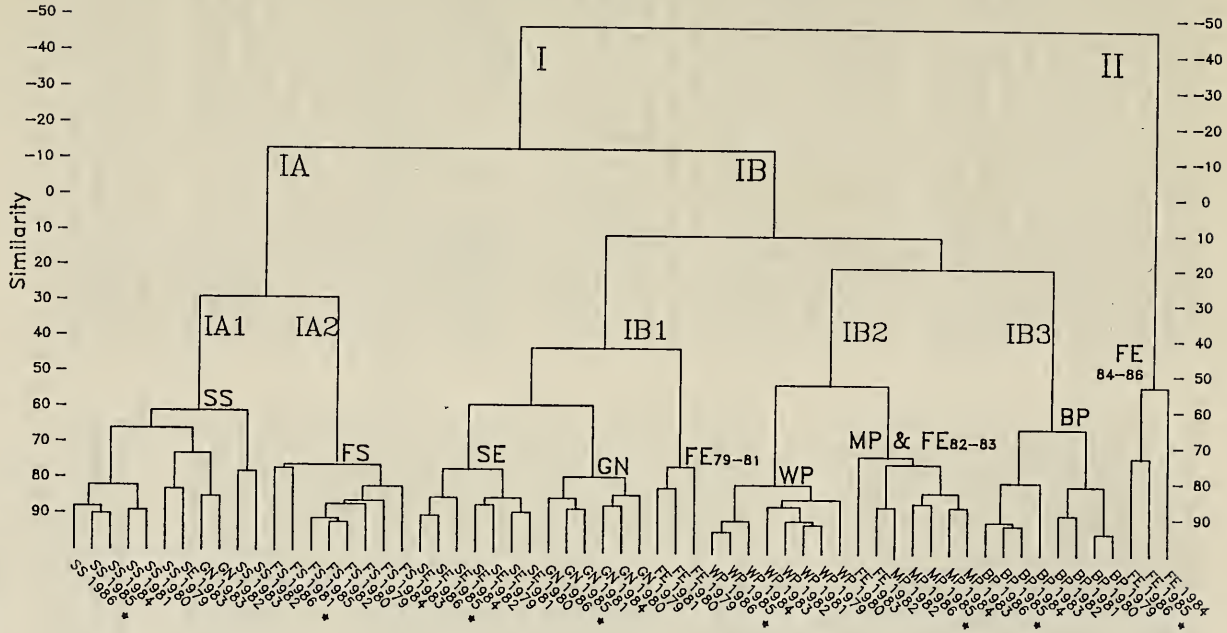

Fig. 4. Clustering dendrogram of similarity, by station and year, 1979-1987. Three-unit operation (March 1986-February 1987) indicated by an asterisk.

reported for the 2-unit operational period (NUSCO 1987), indicating that the local communities, and the factors responsible for structuring them, have remained relatively stable since Unit 3 began operation. Second, the community at Fox Island-Exposed continued to appear dissimilar to those at other rocky intertidal stations. These hypotheses can be tested by analyzing locally prevalent species whose patterns of abundance are important in structuring local intertidal communities (e.g., *Chondrus*, *Fucus*, *Balanus*, *Mytilus*), and those which, although not dominant in terms of percentage of cover, interact with and exert influence on other components of the community (keystone species *sensu* Paine (1966)), e.g., predatory and grazing snails.

Barnacles and predatory snails

Barnacles have been shown to influence the structure of intertidal communities by providing surface heterogeneity and spatial escapes from consumers for settling plants and animals that would otherwise be quickly eliminated from smooth substrata (Lubchenco 1983). Under 3-unit operational conditions, barnacles (mostly *Balanus balanoides*) exhibited a characteristic pattern of abundance. *Balanus* settlement on local shores occurred as early as December-January, but the period of maximum settlement was February-March, earlier than reported for northern New England (Grant 1977). Growth of newly settled barnacles continued through summer, when barnacles occupied almost all available primary space; barnacle abundance ranged from 55% to 95% in Zone 2 in May (Fig. 5). A decline in abundance began in late summer and barnacle coverage was lowest in winter (e.g., 6-45% cover in November, Zone 2). In most cases, the rock surfaces exposed by the mortality of barnacles remained free of macroscopic cover until the following spring. This pattern of barnacle abundance was similar to that observed by Katz (1985) in local populations.

Barnacle abundance varied among stations and zones (Fig. 5). The lowest abundance of barnacles was evident in the high intertidal zone, because of reduced settlement and slower growth due to physical factors such as decreased immersion time and probable desiccation (Menge 1976; Wethey 1985). Sheltered stations such as FS and GN had a lower abundance of barnacles in Zone 1 ($< 10\%$) than at exposed stations such as FE and BP (ca. 30%) where the spray zone increased available moisture for settlement and survival, especially in cracks or crevices that retained moisture. Competition for space was not the limiting factor for barnacle abundance in the high intertidal zone.

Conversely, at times of maximum cover (early summer), barnacles covered virtually all available surfaces in the mid and low intertidal zones, although competition for space with the perennial alga *Chondrus crispus* was responsible for the lower absolute abundance of barnacles in Zone 3 as compared to Zone 2. Particularly in Zone 2, intraspecific competition for space was a source of barnacle mortality. When barnacles settle densely and grow rapidly, they crowd and cannot expand laterally. The consequent upward expansion of the individuals results in relatively small basal areas for attachment, and the hummocks (cf. Connell 1961; Grant 1977) were lost during storms.

Predation by carnivorous snails (most commonly *Urosalpinx cinerea* and *Thais lapillus*) also influences barnacle abundance, especially in the low intertidal zone (Connell 1961; Menge 1976). In the 3-unit operational period to date, *Urosalpinx* (primarily) and *Thais* (to a lesser extent) were present throughout the year, but were most abundant and active in late summer, and in Zone 3. Maximum coverage was less than or equal to 3%, but this population was sufficient to reduce average barnacle cover to ca. 3% by November. Similar predator abundances, and similar control of barnacle populations, have been reported by others (e.g., Menge 1976; Katz 1985).

In general, abundances of barnacles and predatory snails and their seasonal cycles during 3-unit operation were similar to those of the pre-op period. The single exception to these basic trends

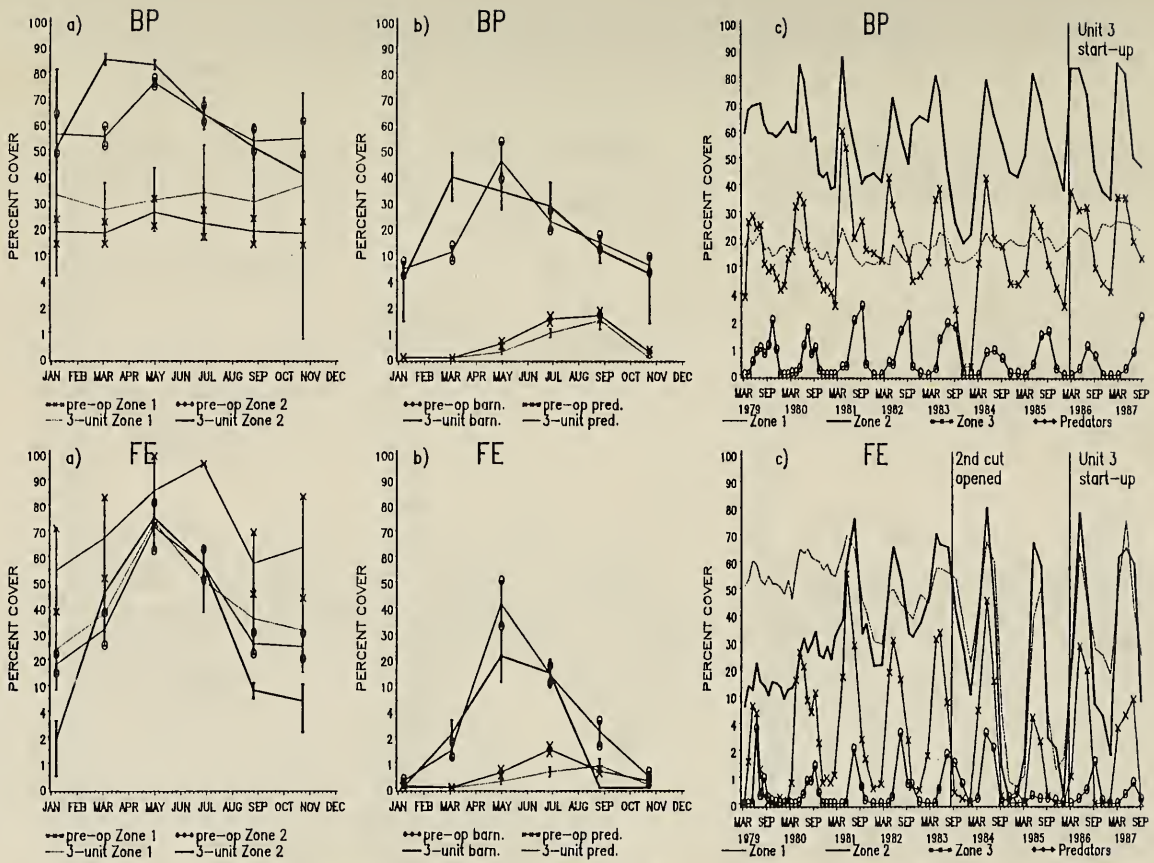

Fig. 5. Abundance of barnacles and predatory snails as percentage of cover in each zone: (a) monthly from 1979-1987, barnacles in Zones 1 and 2, pre-op and 3-unit operation, (b) monthly from 1979-1987, barnacles and predatory snails in Zone 3, pre-op and 3-unit operation, and (c) from March 1979-September 1987, barnacles in each zone and predatory snails in Zone 3.

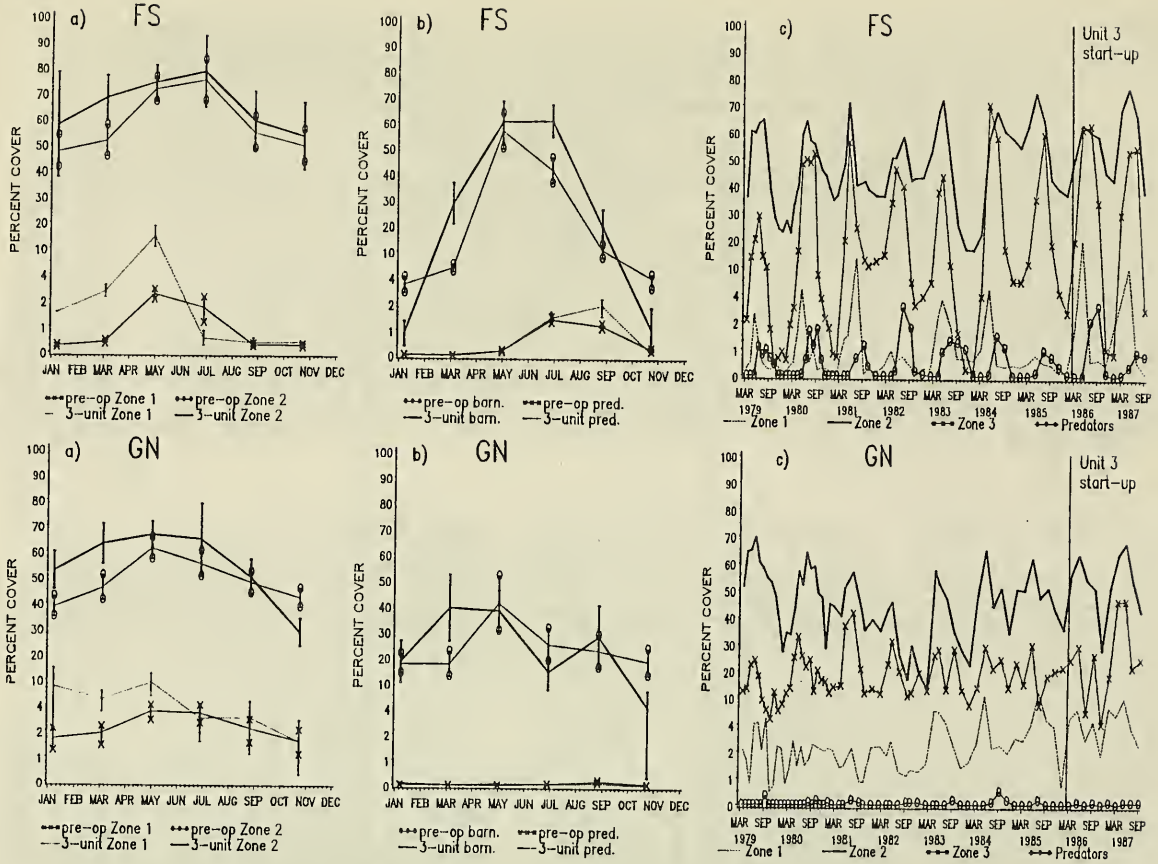
a) FS
b) FS
c) FS
Unit 3 start-up
PERCENT COVER
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
pre-op Zone 1
pre-op Zone 2
3-unit Zone 1
3-unit Zone 2
pre-op born.
pre-op pred.
3-unit born.
3-unit pred.
MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP
1979 1980 1981 1982 1983 1984 1985 1986 1987
Zone 1
Zone 2
Zone 3
Predators
a) GN
b) GN
c) GN
Unit 3 start-up

Fig. 5. (cont.)

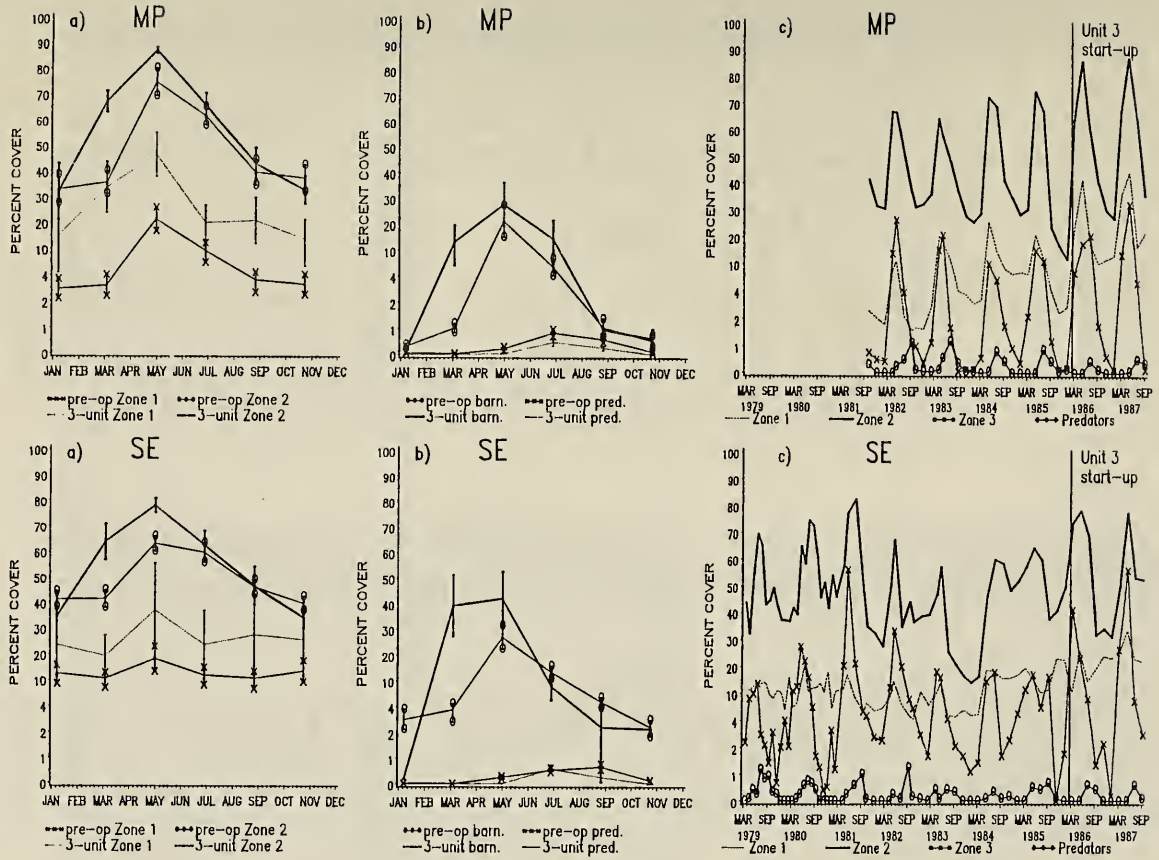
a) MP
b) MP
c) MP
Unit 3 start-up
PERCENT COVER
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
pre-op Zone 1
3-unit Zone 1
pre-op Zone 2
3-unit Zone 2
pre-op barn.
3-unit barn.
pre-op pred.
3-unit pred.
MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP
1979 1980 1981 1982 1983 1984 1985 1986 1987
Zone 1
Zone 2
Zone 3
Predators
a) SE
b) SE
c) SE
Unit 3 start-up

Fig. 5. (cont.)

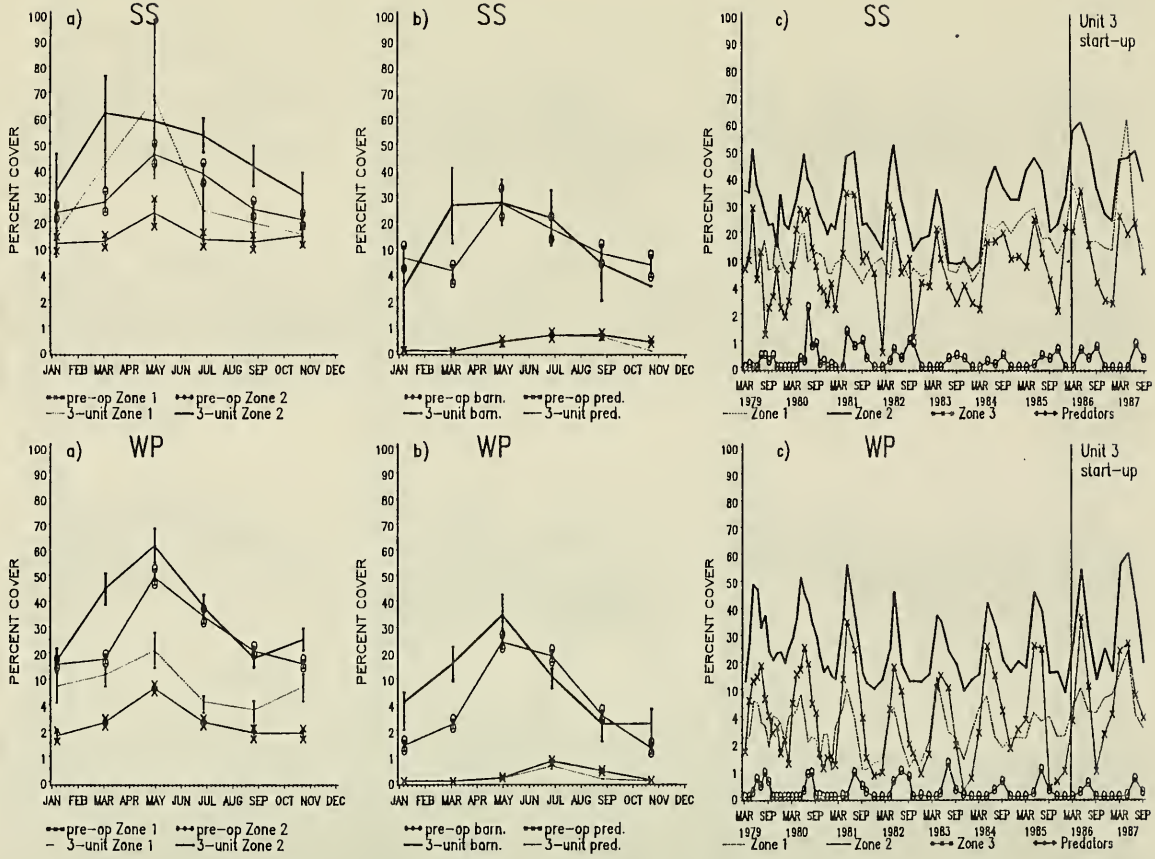
a) SS
b) SS
c) SS
Unit 3 start-up
PERCENT COVER
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
pre-op Zone 1
pre-op Zone 2
3-unit Zone 1
3-unit Zone 2
pre-op barn.
pre-op pred.
3-unit barn.
3-unit pred.
MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP
1979 1980 1981 1982 1983 1984 1985 1986 1987
Zone 1
Zone 2
Zone 3
Predators
a) WP
b) WP
c) WP
Unit 3 start-up

Fig. 5. (cont.)

in local barnacle and predatory snails abundances was the coverage and periodicity observed at FE since September 1984. These changes were related to the opening of the second quarry cut, and attributed to elevated water temperatures (NUSCO 1985, 1986, 1987).

Mussels

Mussels (mostly *Mytilus edulis*) were present at all rocky shore sampling sites during the 3-unit operational period, usually occupying < 5% of the available space (Fig. 6). Mussels typically occurred as clumps of adults in rock crevices where they could persist for long periods (in excess of 20 years, Bayne 1976) or as juveniles that settled among barnacles in mid-summer, but were eliminated by late summer by *Urosalpinx* and *Thais*. One exception to this generality occurred at Seaside Sheltered in July 1986, when 8% of the low intertidal (Zone 3) was covered by a mass of adult mussels that washed into one transect of the study area, presumably after being dislodged from a nearby population. These mussels did not firmly attach themselves and were washed away by the next sampling period. Similar events occurred at SS and SE in 1982 (NUSCO 1983); however, these mussels persisted for as long as two years.

Mussels have not been a dominant component of local rocky shore communities; in the pre-op period, mussel cover exceeded 10% only at Bay Point and Giants Neck. Other researchers in New England have reported that *Mytilus* is superior to *Balanus* as a competitor for available space (e.g., Menge 1976; Grant 1977; Lubchencho and Menge 1978), and as a result dominates intertidal areas. We have also noted the competitive dominance of mussels in exclusion cage studies (e.g., NUSCO 1985, 1987). A common finding of these studies was that mussels could exclude barnacles only when predation pressure was reduced, by physical conditions (e.g., wave shock) or experimental manipulation; these conditions are not representative of the Millstone area.

An atypical pattern of mussel abundance was noted at Fox Island-Exposed (Fig. 6). In both summers of the 3-unit operational period to date, mussels settled densely among barnacles in the mid and low intertidal zones. These mussels grew rapidly and increased coverage to ca. 30%, outcompeting barnacles as they did so. However, the mussels were almost totally eliminated by autumn. Both the initial rapid growth and subsequent high mortality were attributed to elevated water temperature. Incursion of warm water produced optimum growth conditions in early summer; however, maximum temperature for adult survival is reported to be ca. 27°C (Read and Cumming 1967; Bayne 1976; Gonzalez and Yevich 1976). This temperature occurred in the quarry (Schneider 1981; Johnson et al. 1983) and at FE under 3-unit operating conditions.

Fucus

The perennial brown alga, *Fucus vesiculosus*, is found throughout intertidal communities locally, but is especially abundant in the mid intertidal zone (Fig. 7). Growth conditions are optimal in Zone 3, but *Fucus* is usually outcompeted by *Chondrus* (cf. Lubchenco 1980). Station-to-station variability exists in *Fucus* abundance, related to degree of exposure. Consistently low *Fucus* abundance was typical of BP (Zone 2, 0-3% in the pre-op and 3-unit operational periods), an exposed sampling site prone to physical stress caused by storm activity and ice damage. The other stations, however, were more moderately exposed, and reflected conditions suitable for *Fucus* growth (Topinka et al. 1981; Keser and Larson 1984). Overall, average *Fucus* canopy in Zone 2 was about 32%, excluding BP data.

Temporal variability is also evident in local *Fucus* populations. *Fucus* occupies new substrata following settlement of zygotes in spring (Knight and Parke 1950; Keser and Larson 1984), and growth of germlings which achieve peak abundance in late summer. Typically, *Fucus* settles between barnacles and utilizes the spatial escape until it is large enough to be unpalatable to grazing snails (Keser 1978; Geiselman and McConnell

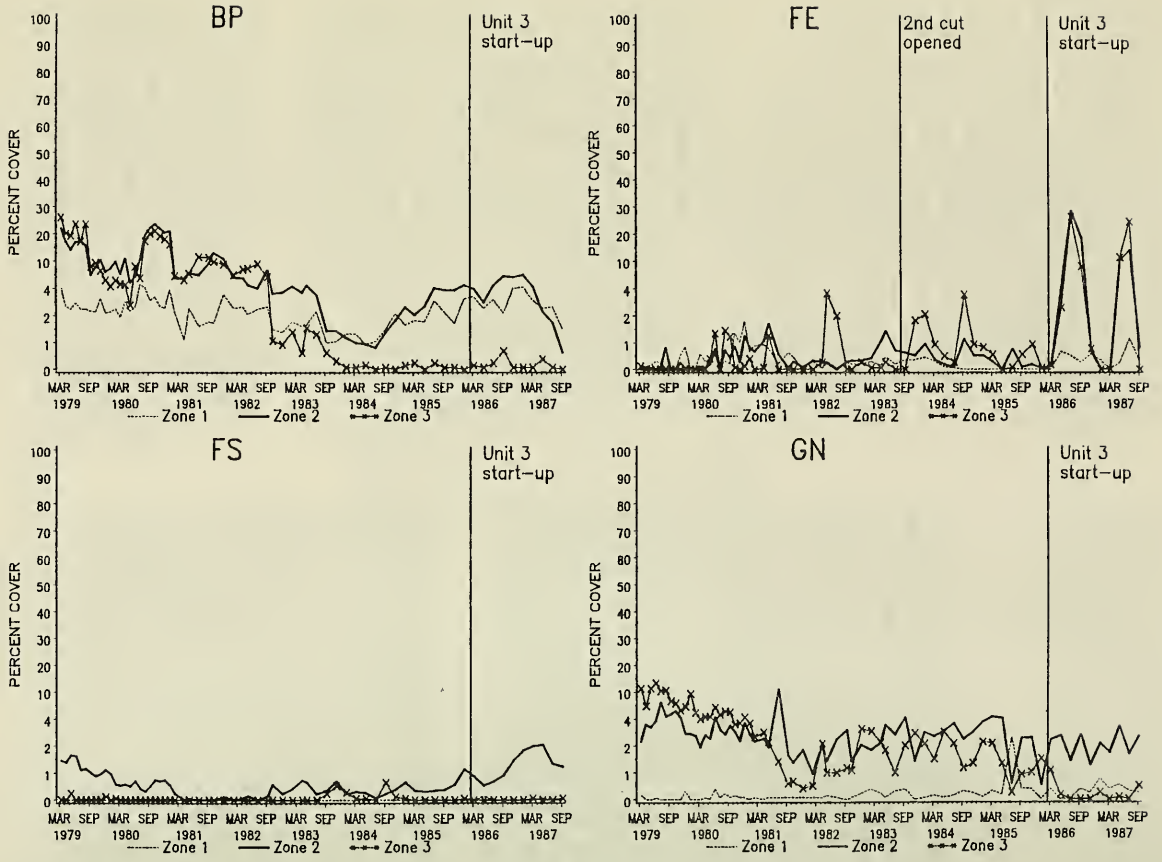

Fig. 6. Abundance of mussels as percentage of cover in each zone, from March 1979-September 1987.

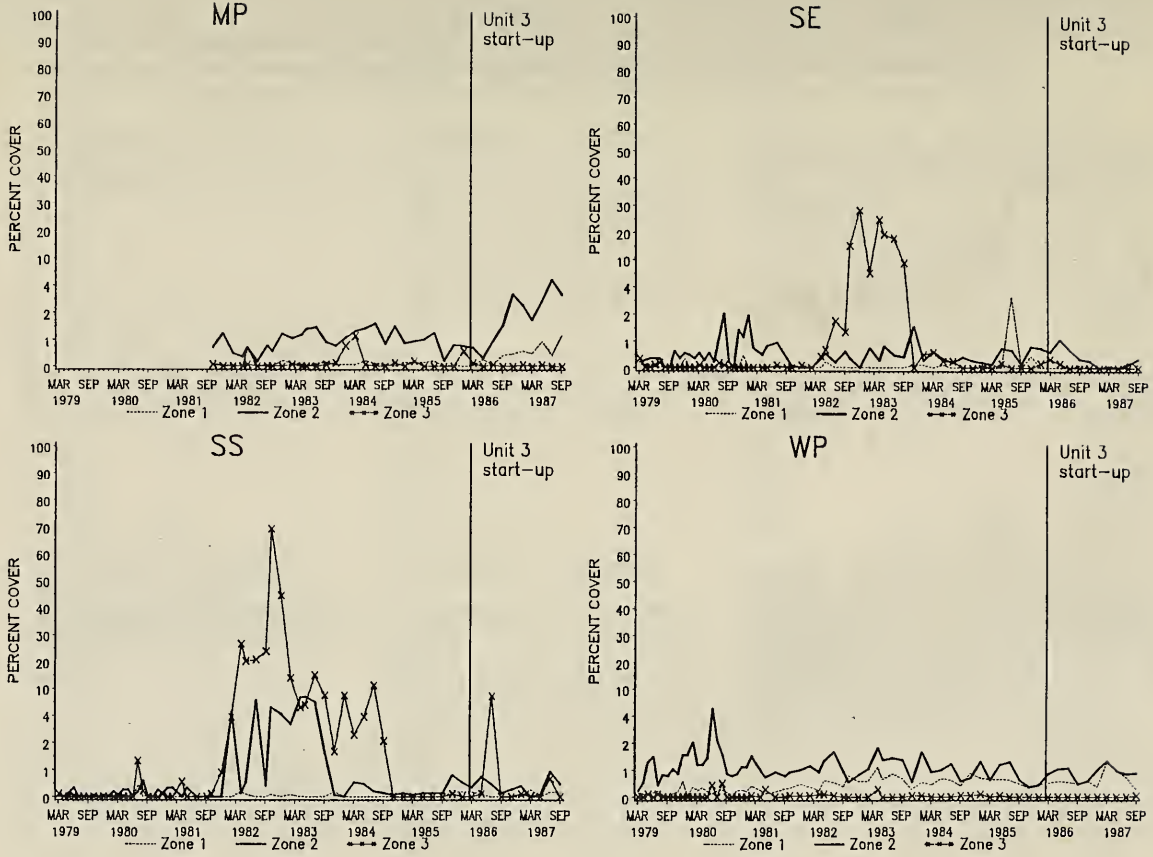
MP
SE
SS
WP
Unit 3
start–up
PERCENT COVER
100
90
80
70
60
50
40
30
20
10
4
2
1
0
MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP
1979 1980 1981 1982 1983 1984 1985 1986 1987
Zone 1
Zone 2
Zone 3

Fig. 6. (cont.)

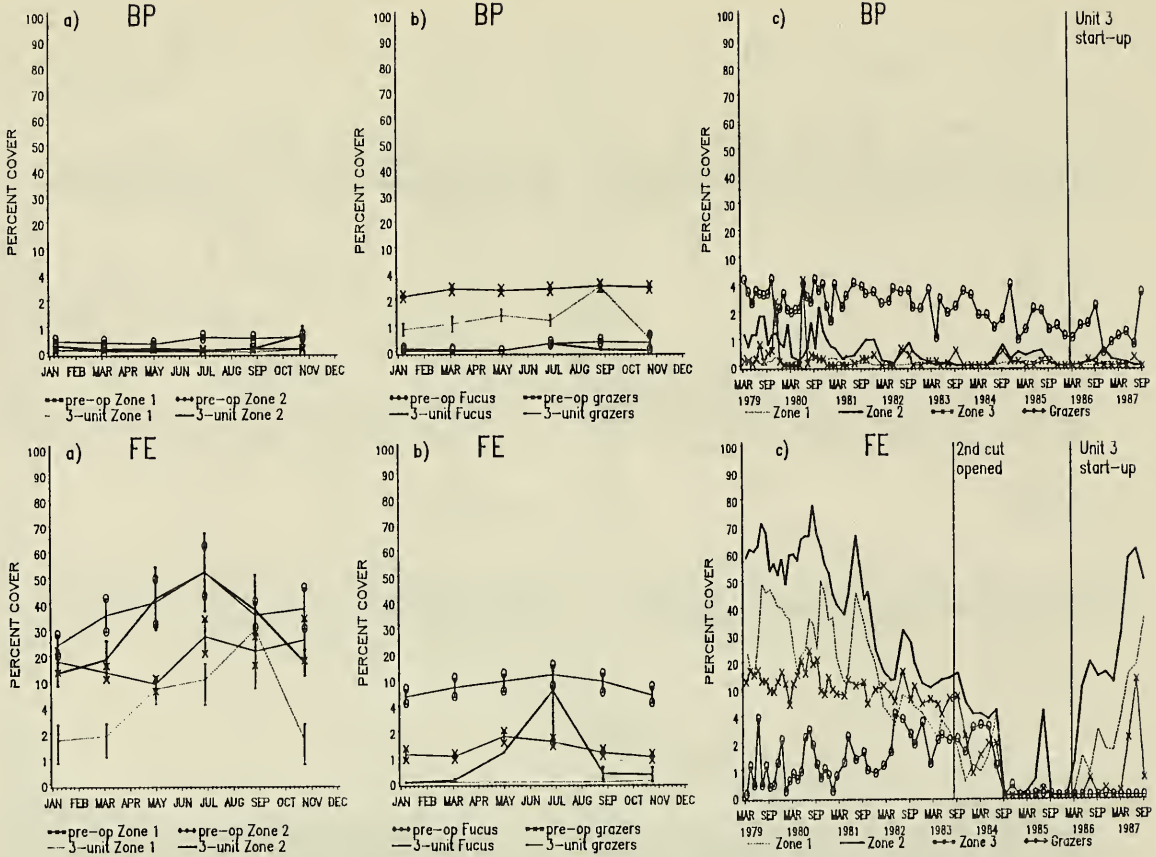

Fig. 7. Abundance of *Fucus* and grazers as percentage of cover in each zone: (a) monthly from 1979-1987, *Fucus* in Zones 1 and 2, (b) monthly from 1979-1987, *Fucus* and grazers in Zone 3, and (c) from March 1979-September 1987, *Fucus* in all zones and grazers in Zone 3.

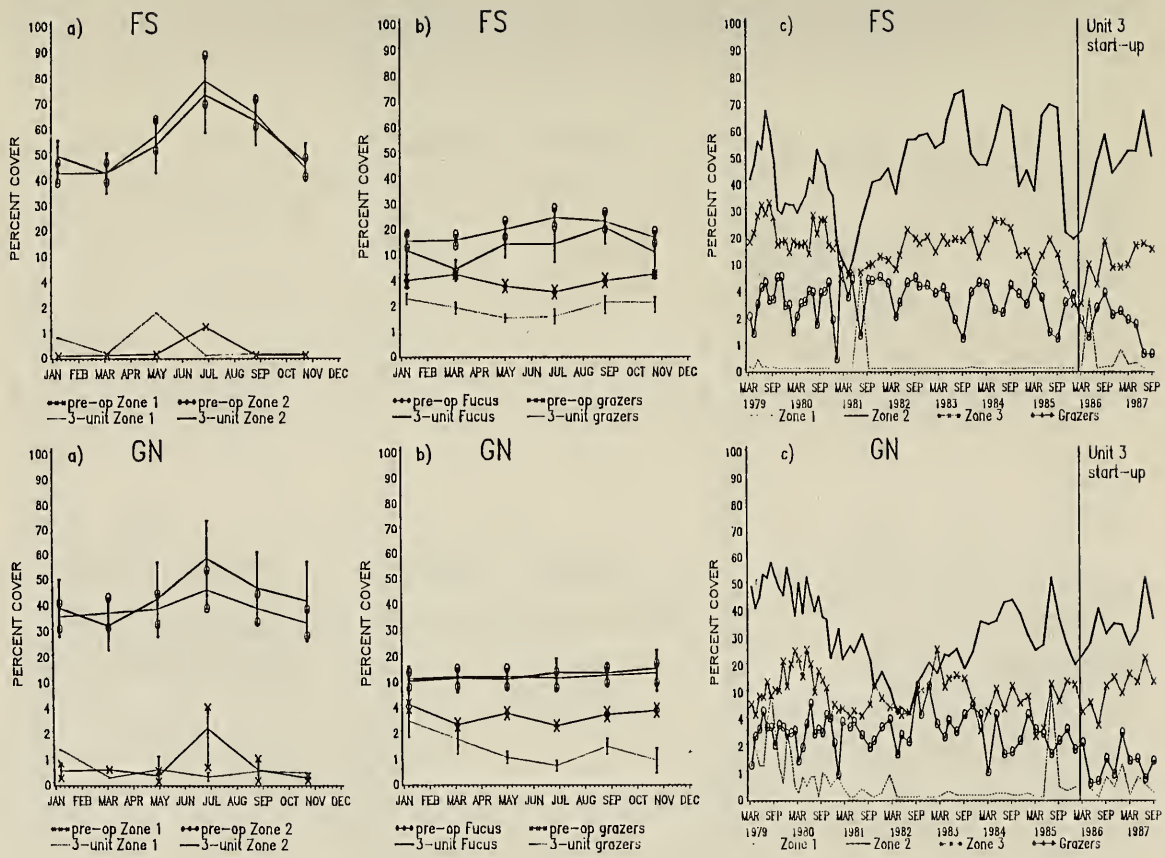
a) FS
b) FS
c) FS
Unit 3 start-up
PERCENT COVER
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
pre-op Zone 1
pre-op Zone 2
3-unit Zone 1
3-unit Zone 2
pre-op Fucus
pre-op grazers
3-unit Fucus
3-unit grazers
MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP
1979 1980 1981 1982 1983 1984 1985 1986 1987
Zone 1
Zone 2
Zone 3
Grazers
a) GN
b) GN
c) GN

Fig. 7. (cont.)

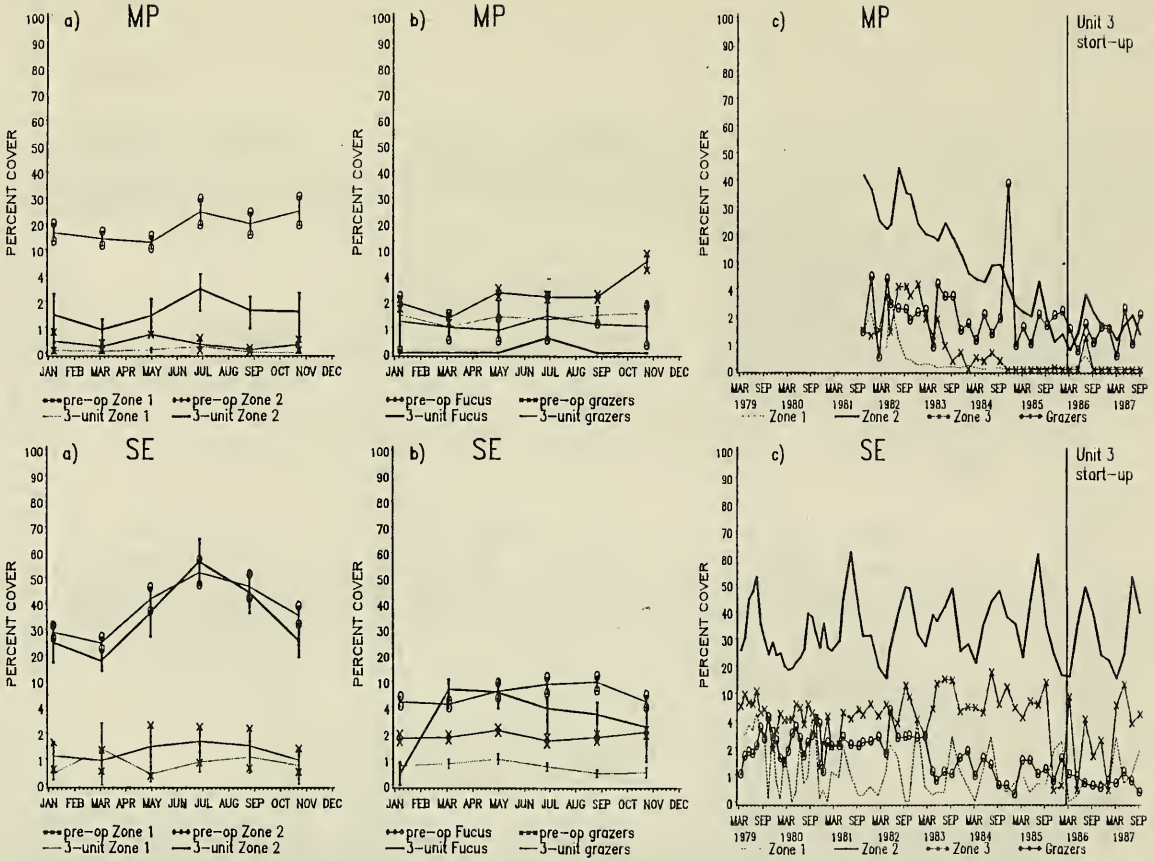
a) MP
b) MP
c) MP
Unit 3 start-up
a) SE
b) SE
c) SE
Unit 3 start-up
PERCENT COVER
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
pre-op Zone 1
pre-op Zone 2
3-unit Zone 1
3-unit Zone 2
pre-op Fucus
pre-op grazers
3-unit Fucus
3-unit grazers
MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP
1979 1980 1981 1982 1983 1984 1985 1986 1987
Zone 1
Zone 2
Zone 3
Grazers

Fig. 7. (cont.)

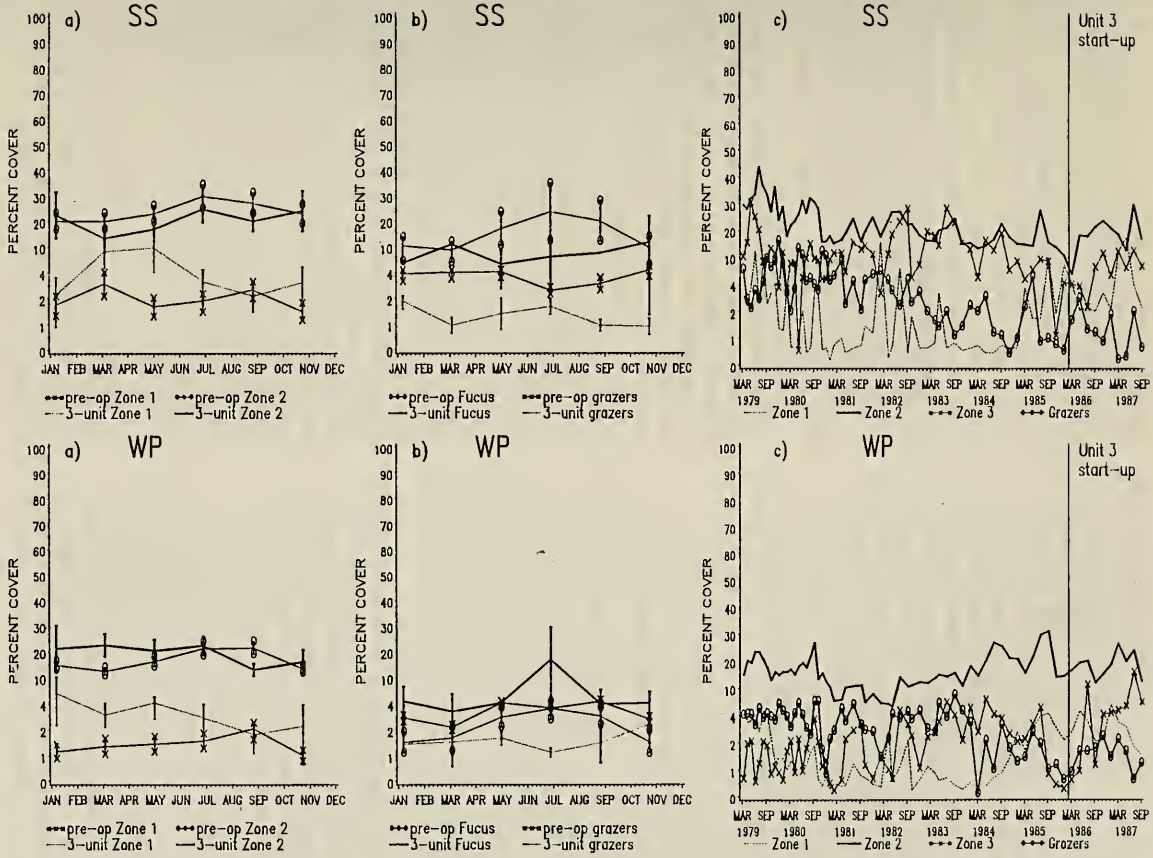
a) SS
b) SS
c) SS
Unit 3 start-up
PERCENT COVER
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
pre-op Zone 1
pre-op Zone 2
3-unit Zone 1
3-unit Zone 2
pre-op Fucus
pre-op grazers
3-unit Fucus
3-unit grazers
MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP
1979 1980 1981 1982 1983 1984 1985 1986 1987
Zone 1
Zone 2
Zone 3
Grazers
a) WP
b) WP
c) WP
Unit 3 start-up

Fig. 7. (cont.)

1981; Lubchenco 1983). The seasonal cycle is seen most clearly at Seaside Exposed. As *Fucus* plants mature, they become increasingly susceptible to epiphytism (Menge 1975), storm damage and ice-scouring (Mathieson et al. 1982; Chock and Mathieson 1983) in autumn and winter. These processes tend to remove many plants at once, opening new substrata for colonization and perpetuating the cycle of *Fucus* abundance (cf. Schonbeck and Norton 1980; Keser and Larson 1984). If these processes operate on a small scale, removal of old plants from one area will be offset by growth of young plants in a nearby area, and the average *Fucus* cover at the station will be relatively stable over time (e.g., SS and WP). If, however, the removal process clears a large area, many zygotes will settle, grow, and senesce in synchrony, and produce a long-term cycle in *Fucus* abundance, based on its 3-5 year lifespan. This phenomenon has been observed locally (e.g., FS and GN) and by other researchers (Niemeck and Mathieson 1976; Keser and Larson 1984).

Pre-op and 3-unit operational *Fucus* populations were similar at most stations in the monitoring program. The mid intertidal zone was dominated by a *Fucus* canopy, and similar spatial and temporal patterns were observed for each operational period. Exceptions to these general trends in *Fucus* abundance were observed at MP and FE in the 3-unit operational period.

Fucus abundance in Zone 2 at MP steadily decreased from 45% in 1982 to 1% just before Unit 3 began operation in 1986; coverage has ranged from 1% to 4% in the 3-unit operational period (Fig. 7). This decrease in *Fucus* abundance was initially interpreted as the descending portion of a long-term *Fucus* cycle, like those seen at FS and at other stations, but more protracted at MP than elsewhere. The delay in increased *Fucus* abundance may be related to grazing pressure; other researchers have shown that high grazer densities can retard *Fucus* recolonization for several years (Lubchenco 1983; Keser and Larson 1984). However, the abundance of grazers was stable for most of the study's duration and similar to that at other stations, despite high densities of *Littorina littorea* at MP in November 1984 (over 50% cover in some quadrats). Continual low *Fucus* abundance at MP may be related to water temperature; however, Kanwisher (1966) showed that adult *Fucus* can tolerate temperatures up to 30 °C without thermal injury, and maximum water temperatures measured at MP were ca. 25 °C. To more fully understand the processes occurring at MP, a schedule of temperature measurement will be developed and a series of exclusion cages is planned in spring 1988. As this site is the second-closest station to the discharges, continued monitoring is needed to determine if MP could be subjected to thermal effects during 3-unit operation.

Fucus abundance at FE has undergone substantial changes since the inception of the monitoring program. *Fucus* coverage was very high from 1979 to 1981 (e.g., averaged ca. 60% cover in Zone 2; Fig. 7) and gradually decreased to low abundance (ca. 15% cover in July 1983, ca. 6% cover in July 1984), suggestive of the descending portion of the local 3-5 year *Fucus* abundance cycle. The thermal impact resulting from 2-unit/2-cut operation caused elimination of the *Fucus* population at FE in September 1984, consequently interrupting the *Fucus* population cycle; the expected increase in *Fucus* cover following settlement of zygotes in spring 1984 was not seen. The abundance of grazers at FE prior to thermal impact was similar to that measured at other rocky intertidal stations, but grazers have been virtually nonexistent at FE since the time of impact; therefore, the failure of *Fucus* to recover was not due to grazing pressure. Lethal effects of high water temperatures on *Fucus* populations have been discussed in past annual reports (NUSCO 1985, 1986, 1987) and by other researchers (e.g., Kanwisher 1966; Vadas et al. 1976). *Fucus* settled in spring 1985, reached about 6% cover, then was eliminated in late summer. *Fucus* zygotes settled the following spring (1986, beginning of the 3-unit operational period) and germlings grew to achieve a higher abundance (ca. 20% in Zone 2) in summer. These plants survived and eventually reached a peak abundance of over 60% in summer 1987. It is apparent that summer conditions at FE, as

well as the shoreline between FE and the discharges, approach the physiological limits for survival of *Fucus*. It is likely that slight changes in summer maximum ambient water temperatures, and plant operating levels during critical periods, will affect the *Fucus* population at FE.

Chondrus

Chondrus crispus is a bushy, perennial red alga that is the dominant species in the low intertidal zone at most stations. *Chondrus* contributes to community stability by maintaining extensive populations through time. In both pre-op and 3-unit operational periods, *Chondrus* occupied from 4-80% of the Zone 3 substrata (average ca. 45%, Fig. 8 a,c), excluding FE which is discussed separately. Station-to-station variability of *Chondrus* abundance existed; MP and WP showed consistently high (70-80%), and FS consistently low (ca. 10%) *Chondrus* abundance in Zone 3 for both operational periods.

Chondrus grows as a clump of upright stalks from a basal crust; longevity of the stalks is 2-3 years, and the crust may live 6 years or longer (Ring 1970; Taylor and Chen 1973). Young stalks continually grow up to replace old ones that are lost. Occasionally, processes occur that remove stalks of all ages. A period of extremely low tides concurrent with extremely cold temperatures in February 1980 exposed *Chondrus* to lethal conditions (NUSCO 1982, 1983), and was responsible for the general decline in local *Chondrus* abundance in the following spring. Similar events, on a smaller scale, have occurred in nearly every winter of our study. Regrowth from surviving crustose holdfasts occurs relatively quickly (Prince and Kingsbury 1973), maintaining *Chondrus* as the dominant species in the low intertidal zone at most rocky intertidal sampling stations.

If the basal crust of *Chondrus* is damaged or removed, recovery of the population is much slower, on the order of 3-5 years (Ring 1970; Lubchenco 1980; NUSCO 1987). This extent of damage was seen only at Fox Island-Exposed. When temperatures exceeded 28 °C at FE in September 1984, *Chondrus* was eliminated from the community and was replaced by opportunistic, ephemeral algae; the subsequent community was described in detail in past annual reports (NUSCO 1985, 1986, 1987). *Chondrus* has not re-established itself at FE since September 1984, and has only appeared in one low intertidal quadrat as a few young fronds in summer 1987 (Fig. 8). *Codium fragile*, a green alga, is now the dominant component of the FE community, especially in the low intertidal zone. Upright portions of *Codium*, like *Chondrus*, are vulnerable to freezing and winter fragmentation (Fralick and Mathieson 1972; Ramus 1972), but, also like *Chondrus*, the surviving basal portion can regenerate new uprights in spring. Unlike *Chondrus*, *Codium* can tolerate the maximum summer temperatures measured at FE.

Chondrus serves as substratum for a large variety of epiphytic plants and animals. In some cases, this epiphytism has been found to cause shading that is harmful to underlying *Chondrus* (Menge 1975; Lubchenco and Menge 1978), and for this reason the abundance of two major epiphytes on *Chondrus*, *Monostroma* and *Polysiphonia*, is presented for discussion. *Monostroma* shows peaks of abundance in spring, March-May (Fig. 8). Maximum cover at most stations is 5-10%; at FS, peaks are only 1-2% (owing to lack of *Chondrus*), and at SE, peaks are 20-40%. At FE, maxima prior to the opening of the second cut were 20-40%, and zero subsequently. Abundance of *Polysiphonia* peaks in autumn, August-October, with maxima comparable to that of *Monostroma*. Again, the seasonal periodicity was disrupted at FE.

Fox Island-Exposed was the only station in either the pre-op or 3-unit operational period where *Chondrus* and epiphytes were affected by elevated water temperature. Like *Chondrus*, *Monostroma* has not returned to FE; its absence began in spring 1984, probably as the result of increased competition for space with *Polysiphonia* after the second quarry cut was opened in August 1983. Abundance of *Polysiphonia* peaked at 55% in

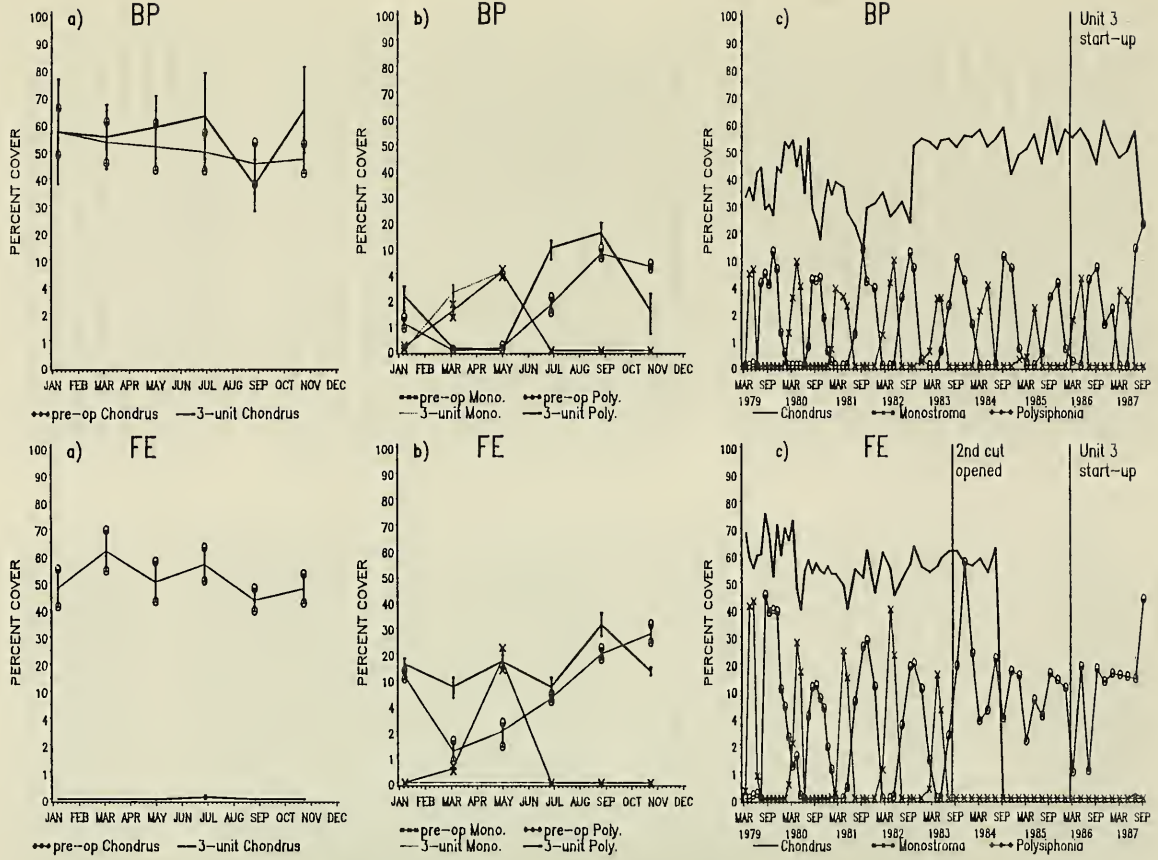

Fig. 8. Abundance of *Chondrus* and major epiphytes as percentage of cover in Zone 3: (a) monthly from 1979-1987, *Chondrus* in Zone 3 (b) monthly from 1979-1987, *Monostroma* and *Polysiphonia* in Zone 3, and (c) March 1979-September 1987, *Chondrus*, *Monostroma*, and *Polysiphonia* in Zone 3.

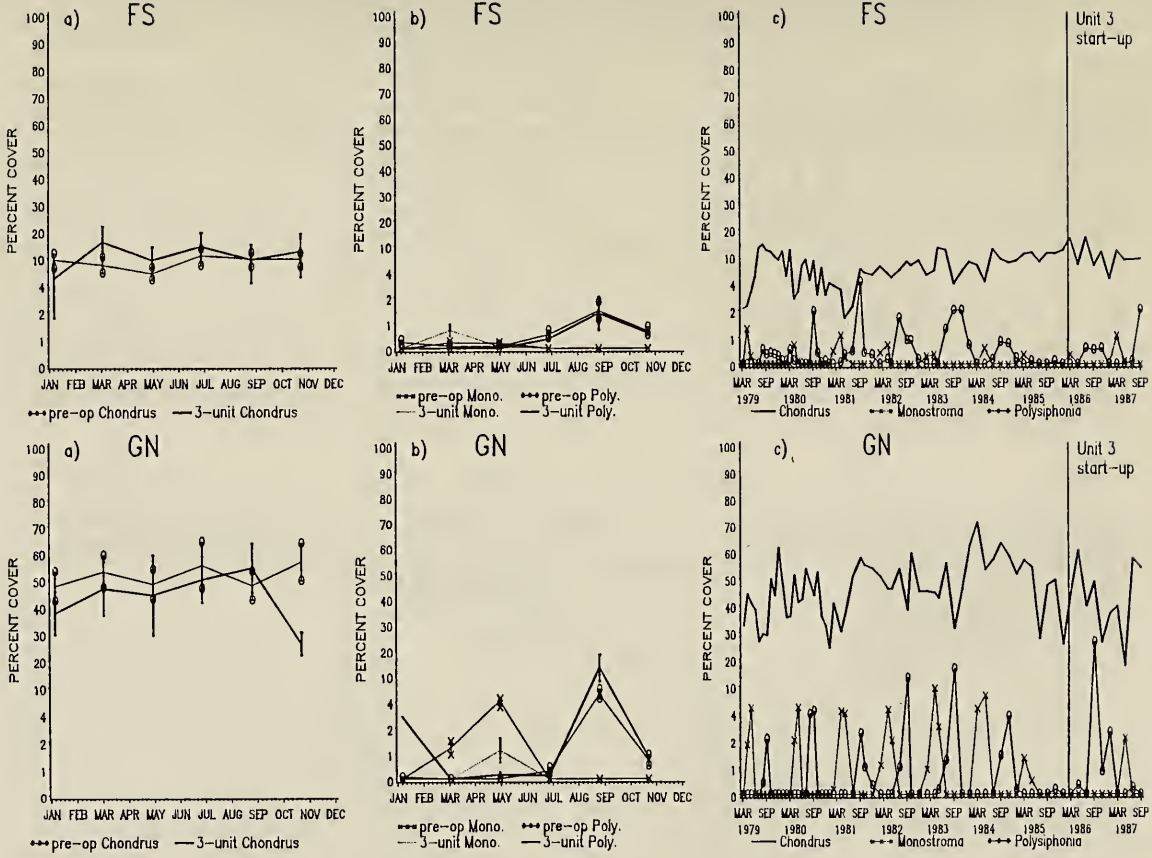
a) FS
b) FS
c) FS
Unit 3 start-up
PERCENT COVER
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
pre-op Chondrus
3-unit Chondrus
pre-op Mono.
3-unit Mono.
pre-op Poly.
3-unit Poly.
MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP
1979 1980 1981 1982 1983 1984 1985 1986 1987
Chondrus
Monostroma
Polysiphonia
a) GN
b) GN
c) GN
Unit 3 start-up

Fig. 8. (cont.)

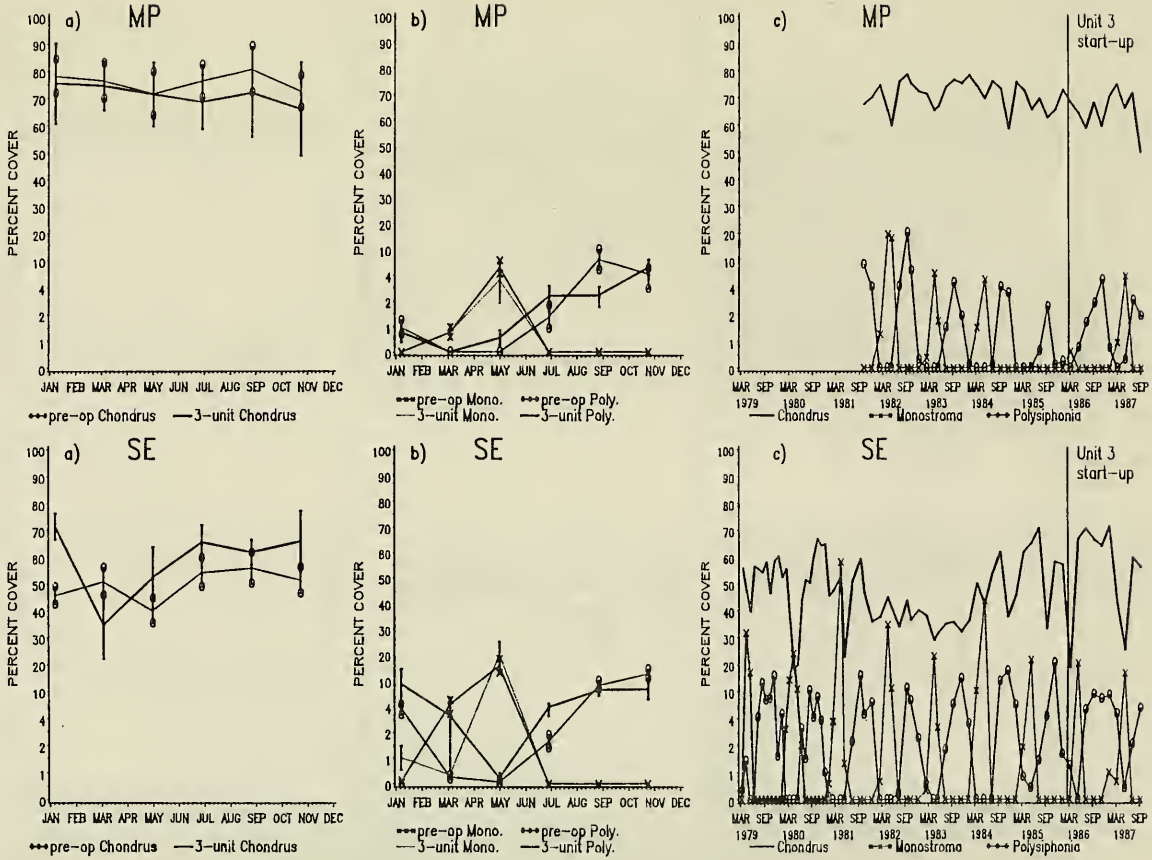
a) MP
b) MP
c) MP
Unit 3 start-up
PERCENT COVER
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
pre-op Chondrus
3-unit Chondrus
pre-op Mono.
3-unit Mono.
pre-op Poly.
3-unit Poly.
MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP
1979 1980 1981 1982 1983 1984 1985 1986 1987
Chondrus
Monostroma
Polysiphonia
a) SE
b) SE
c) SE

Fig. 8. (cont.)

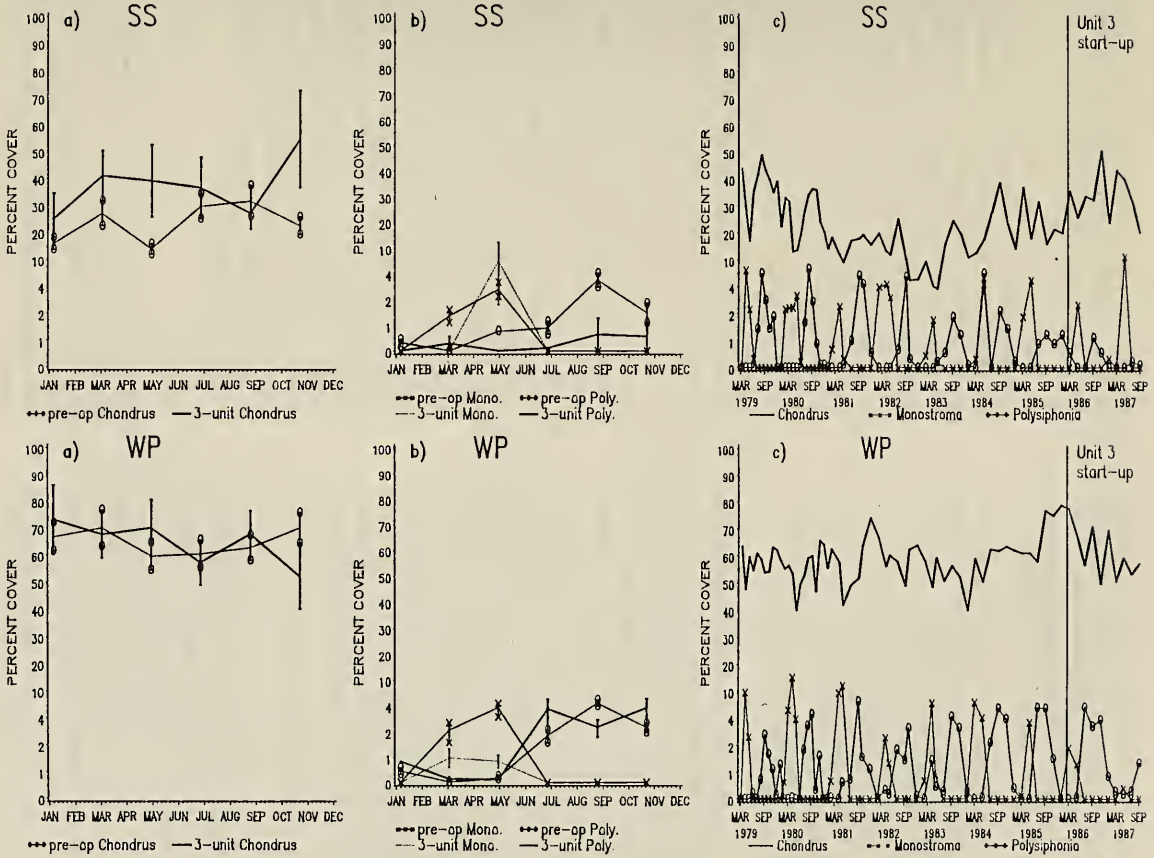
a) SS
b) SS
c) SS
Unit 3 start-up
PERCENT COVER
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
pre-op Chondrus
3-unit Chondrus
pre-op Mono.
3-unit Mono.
pre-op Poly.
3-unit Poly.
MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP MAR SEP
1979 1980 1981 1982 1983 1984 1985 1986 1987
Chondrus
Monostroma
Polysiphonia
a) WP
b) WP
c) WP
Unit 3 start-up

Fig. 8. (cont.)

November 1983, and has maintained relatively high abundance since. The seasonal periodicity of *Polysiphonia* noted throughout the area, including FE prior to the opening of the second quarry cut, has not been seen at FE subsequently.

Monostroma coverage at MP decreased from spring 1984 through winter 1986, which may have indicated a thermal effect of the 2-unit/2-cut plume since MP is the second closest station to the MNPS discharge. Also, *Monostroma* abundance at WP was atypically low in spring 1987 possibly indicating influence of the 3-unit plume. Further monitoring will allow us to determine whether these events represent natural variability or an indication of thermal incursion.

To summarize, rocky intertidal quantitative data collected during 3-unit operation were within pre-op ranges at most stations. Spatial and temporal abundance patterns of local species have been established and are similar to those observed by other researchers in New England (e.g., Menge 1975; Menge 1976; Grant 1977). Seasonality, degree of exposure, and competition induced variability in community parameters. The structure of the Fox Island-Exposed community changed after September 1984 when water temperatures exceeded 28 °C, the upper physiological limit of most species present. The FE community had not re-established itself to pre-impact levels by September 1987 (3-unit operation), and it is not expected to under existing thermal fluctuations described in the Temperature section of this report.

Recolonization Studies

Natural perturbations to established communities of attached plants and animals result in free space for recolonization, and are an on-going process in intertidal communities. Factors that determine rate of recovery following perturbation include physical or physiological stress, grazing and predation, species competition, and temporal and spatial heterogeneity (Dayton 1975). In addition, life-history stages, degree of exposure, and time of denuding can determine rate of recolonization in intertidal communities. These recolonization studies, therefore, simulate natural processes, and allow examination of the factors that influence community recovery.

Previous studies (e.g., NUSCO 1985) have shown that rates and patterns of recolonization, especially in the first year following denuding, may be characterized by patterns of recovery of two major groups that distinguish local intertidal communities: *Balanus balanoides* and *Fucus vesiculosus*. *Chondrus crispus*, the dominant alga in the low intertidal zone of undisturbed areas, has not recolonized the denuded transects adequately in the first 12 months to warrant inclusion in this report. Preliminary data from the 1986 autumn denuding are compared to the 1981 autumn denuding; these data will be updated in subsequent reports. Recolonization transects data are compared to undisturbed transects data for each site to show rate and extent of recovery.

Rates of community recovery are related to intertidal height, and to the complexity of species assemblages found in each zone. The high intertidal zone consists mostly of barnacles on otherwise bare rock (or occasionally, blue-green algae and ephemerals, which can appear in high intertidal areas within days of denuding) and therefore appears recovered, or similar in appearance to undisturbed areas, by the end of the first barnacle set. On the other hand, the low intertidal zone is dominated by *Chondrus* and associated epiphytes; as noted earlier, *Chondrus* recovery on denuded substrata is slow, and it may take at least several years before Zone 3 recolonization quadrats resemble nearby undisturbed areas. Rates of recovery in the mid intertidal zone are intermediate; therefore, this report will emphasize data only from Zone 2.

Barnacles

Recolonization of barnacles was observed in spring in all recolonization transects after both autumn denuding experiments. Annual peak barnacle abundance, occurring in early summer, was very similar in undisturbed and recolonization transects at the four recolonization sites; peak

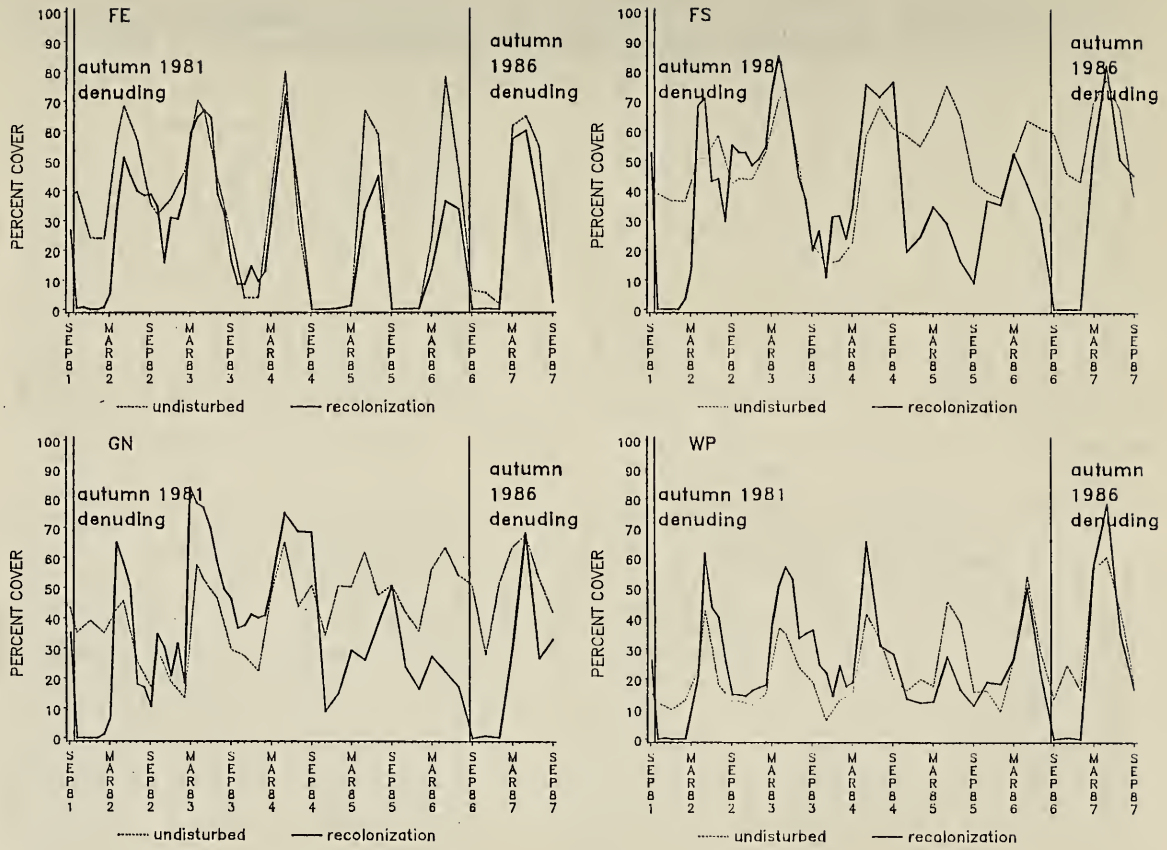

Fig. 9. Abundance of *Balanus* at recolonization sites in Zone 2, from September 1981-September 1987. Vertical lines represent time of denuding.

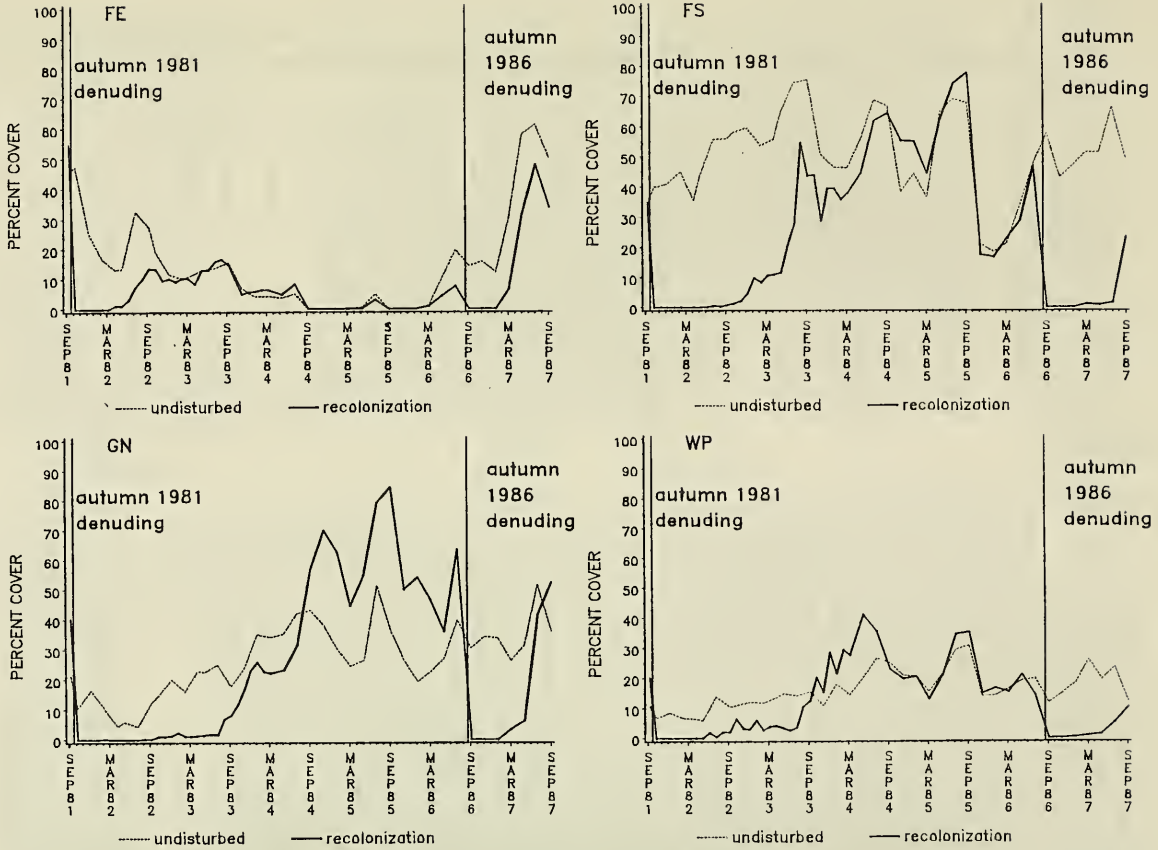

Fig. 10. Abundance of *Fucus* at recolonization sites in Zone 2, from September 1981-September 1987. Vertical lines represent time of denuding.

abundance in Zone 2 ranged between 60-85% (1986, 3-unit denuding) and 50-70% (1981, 2-unit denuding) in the recolonization transects and between 60-80% (1986) and 45-70% (1981) in the undisturbed transects (Fig. 9). In terms of barnacle abundance, recovery of the mid intertidal zone occurs in less than a year, soon after first settlement; populations in the recolonization transects were equal in abundance to those in nearby undisturbed transects.

Recent barnacle abundance patterns in the recolonization transects at FE, while similar to those of FE undisturbed areas (Fig. 9, FE), were different from those of other stations and also different from those seen at FE following the autumn 1981 denuding. Barnacle coverage decreased to < 5% in both the recolonization and undisturbed transects by September 1987. Some species (e.g., *Mytilus* and *Codium*, noted in the previous section) outcompeted barnacles for available substrata in late summer. Again, these differences were associated with the opening of the second quarry cut, not Unit 3 start-up.

Fucus

Local *Fucus* recolonization was not evident until the spring following the autumn denudings. *Fucus* (mostly *Fucus vesiculosus*) settled in spring and rapid growth was evident in summer (Fig. 10). Recovery of the *Fucus* population to undisturbed levels following the autumn 1981 denuding (2-unit operation) took from 15-36 months (Fig. 10; NUSCO 1984, 1985). Following the autumn 1986 denuding, recovery was faster; by September 1987, *Fucus* abundance in the recolonization transects approached or exceeded that in the undisturbed transects at each station but FS. Even at FS, the *Fucus* cover 12 months after the 1986 denuding (25%) was much more extensive than 12 months after the 1981 denuding (2%). The difference between *Fucus* recolonization after the 1981 and 1986 denudings was attributed to year-to-year variability in *Fucus* zygote settlement and survival, as the pattern was consistent throughout the study area.

After the 1986 autumn denuding, major groups of species recolonized at different rates and patterns, dependent on several factors such as life-history stages. Simpler, faster-growing, opportunistic algal species are initially superior in colonization to the more complex, slower-growing perennial species. Denuded areas near local established communities were most rapidly colonized by ephemeral species, characterized by having long reproductive seasons, rapid growth rates, high productivity, and simple thallus forms (Littler and Murray 1974; Connell 1975; Littler and Littler 1980). Because of their availability, ephemerals always initiated the sequence of recolonization in all intertidal zones at exposed and sheltered sampling sites. *Balanus* and *Fucus* settled next in spring, and achieved peak abundance in summer. *Chondrus*, because of competition with *Fucus* (and removal of *Chondrus* holdfasts when the area was denuded), recolonizes at a slow rate, and may require more than 30 months to recover (cf. 1981 autumn denuding, NUSCO 1985, 1986). Continued monitoring of recolonization transects will track the recovery rates of these major intertidal species during the 3-unit operational period.

Ascophyllum nodosum Studies

Since 1979, the rocky intertidal monitoring program has included studies of *Ascophyllum nodosum*, a large perennial alga that is abundant in the low and mid intertidal areas locally. *Ascophyllum* has been studied extensively throughout its range, and its vegetative and reproductive phenology is well documented (David 1943; Printz 1959; Baardseth 1970a; Sundene 1973; Mathieson et al. 1976; Wilce et al. 1978). *Ascophyllum* growth rate has been shown to be sensitive to water temperature changes, especially increases to ambient temperature (Vadas et al. 1976, 1978; Stromgren 1977; Wilce et al. 1978; Keser and Foertch 1982). Because of the alga's response to water temperature change and its mode of linear growth, it has been used to evaluate the thermal effects of power plants in New England (e.g., Maine Yankee, Pilgrim) and is an important biomonitoring tool in the MNPS rocky intertidal program. Extensive discussions of local

Ascophyllum populations have appeared in past reports (NUSCO 1985, 1986, 1987; Ecological Significance of Community Changes at Fox Island - Appendix RSIV in 1987 annual report). Growth and mortality characteristics of local *Ascophyllum* populations, particularly under 3-unit operating conditions, are discussed below.

Growth

Ascophyllum growth was greater at FN (experimental station) in the 3-unit operational period (the 1986-87 growing season) than at the control sites, WP and GN (Fig. 11a). Growth was not linear; length data closely fit a Gompertz growth function. This model assumes an upper limit to size (asymptote, α-parameter), which in our study represents the maximum tip length after a growing season. The other model parameters define an inflection point (i.p.), that represents the time of peak growth rate. The Gompertz model has been applied to numerous biological systems (e.g., Ricker 1975; Draper and Smith 1981), as well as lobster and winter flounder growth in this report; it is an excellent descriptor of *Ascophyllum* tip length vs. time in the present study. Growth at Fox Island was fastest in early spring and peaked 2 weeks earlier than at control sites; for the remainder of the year growth rate was not significantly different between experimental and control site plants. The asymptote of the Gompertz growth model corresponded to an average tip length of 98 mm at FN and 86 mm at both WP and GN, but due to the low number of surviving plants and tips, variability was high and the differences in total growth were not statistically significant.

Similar growth responses were seen under pre-op (1979-86) conditions. The *Ascophyllum* populations at the control sites had similar growth rates and average tip lengths (Fig. 11b). Fox Island *Ascophyllum* plants grew faster and longer (110 mm) than plants at either of the control sites (84-89 mm). Longer tips at Fox Island resulted from higher growth rates in spring, with the point of maximum growth reached 2 weeks earlier than at control sites, thus causing the *Ascophyllum* population at Fox Island to have growth that was significantly different (99% probability) from the growth of WP and GN populations. Growth rate during the remainder of the year was similar for all sites. When within-station comparisons are made, growth responses to temperature changes can be better determined.

Pre-op data at FN exists for only one year, as this station was established in spring 1985. However, to better characterize the response of an *Ascophyllum* population exposed to elevated water temperatures, we have included data from the original experimental station. Thus, Fox Island pre-op growth data are divided into three periods, representing three thermal regimes: FI pre (1979-84), FL (1984-85), and FN (1985-86). Three-unit operational data for FN are referred to as 3-unit (1986-87). These four groupings for Fox Island *Ascophyllum* populations are illustrated in Fig. 12a.

Ascophyllum plants (tips) at Fox Island grew longer than those at WP or GN during all thermal regimes in the pre-op period. At Fox Island, the point of maximum annual growth was reached earlier in the pre-op period than in the 3-unit operational period, and earliest in the 1984-85 thermal regime (May 9, ca. 25 mm in the first month). Warmer than ambient temperatures at FL (2-3 °C warmer under 1-unit, 1-cut conditions in spring 1983; 12-13 °C warmer under 2-unit, 2-cut conditions in spring 1984) and at FN (0-2 °C warmer under 2-unit, 2-cut conditions in spring 1985) enhanced growth because optimal temperatures for *Ascophyllum* growth existed for longer periods of time. However, in summer 1984 temperatures at FL exceeded 28 °C and *Ascophyllum* plants died when their physiological limits were exceeded.

Ascophyllum growth at the new sampling station (FN) in the 3-unit operational period to date (1986-87) was similar to that seen in the single pre-op growing season for which there is growth information (1985-86). Under 2-cut/3-unit operation, these plants were exposed to water temper-

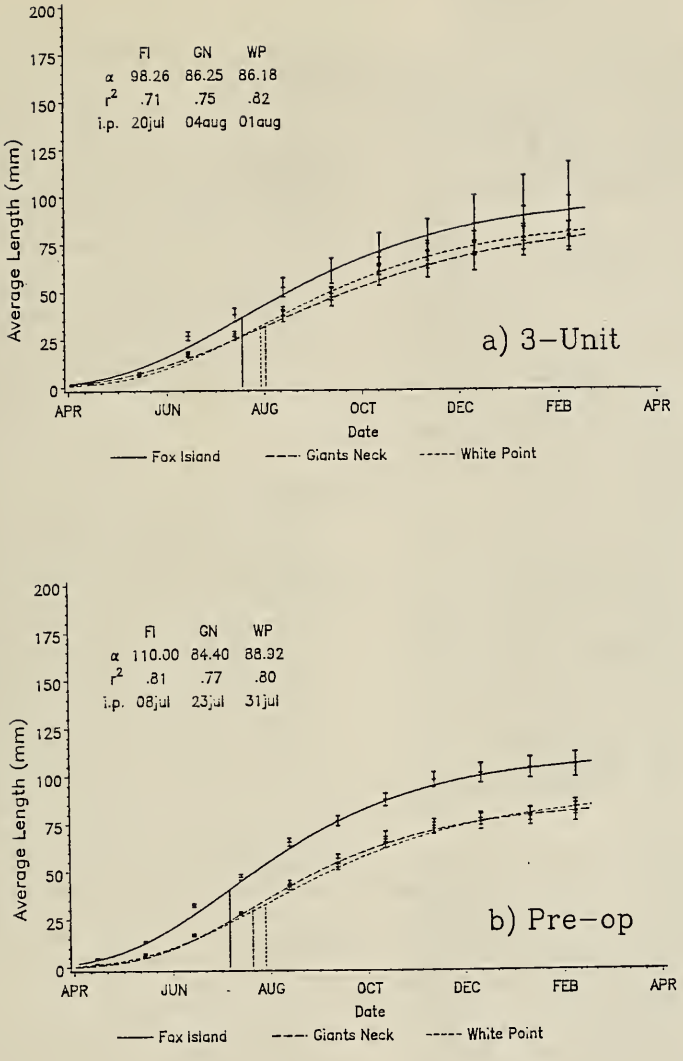

Fig. 11. *Ascophyllum* growth under (a) 3-unit operational and (b) pre-operational conditions. Curve corresponds to the Gompertz growth model fitted to the data, and including inflection points (i.p.) as vertical lines. Error bars represent monthly mean lengths ±2 SE.

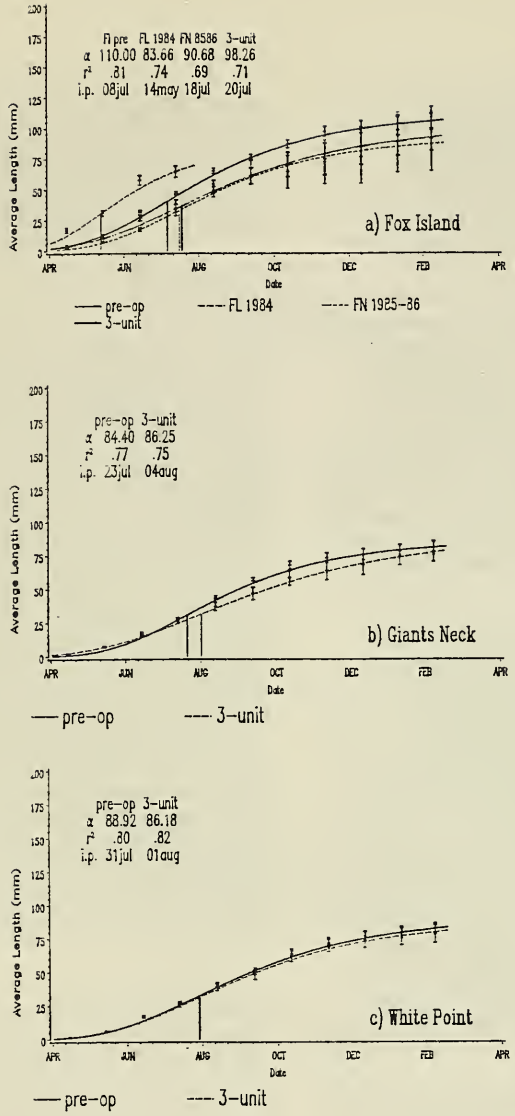

Fig. 12. *Ascophyllum* growth, under pre-operational and 3-unit operational conditions: (a) Fox Island, (b) Giants Neck, and (c) White Point. Curve corresponds to the Gompertz growth model fitted to the data, and including inflection points (i.p.) as vertical lines. Error bars represent monthly mean lengths ±2 SE.

atures 3-4 °C above ambient for 4-5 hours per tidal cycle.

Ascophyllum growth patterns at the control sites have remained consistent throughout the pre-op and 3-unit operational periods (Figs. 12b and c). Total lengths (84-89 mm) and periods of peak growth (late July) were similar between stations and between operational periods.

In summary, local *Ascophyllum* populations have not been affected by operation of Unit 3 to date. Growth rates were similar to those reported for *Ascophyllum* throughout its geographical range (cf. Vadas et al. 1976, 1978; Stromgren 1977; Wilce et al. 1978).

Mortality

Ascophyllum mortality, determined as thallus breakage, is a result of mechanical and environmental stress. Thallus breakage could occur below the base tag, between the base tag and the colored tie wrap used as a tip tag, or between the tip tag and the growing apex. Our measure of tip mortality represents either loss of the tip tag, or loss of all viable apices on a tagged tip. Loss of tip tags implies mechanical removal and immediate loss of plant material. Loss of viable apices and/or damage to the apical cell implies a potential loss of biomass due to lack of growth.

Locally, mortality is variable from year to year. Factors that contribute to mortality include degree of exposure, grazing, wave-force and movement, temperature, competition for space, increased drag due to epiphytization, ineffective reproduction, and thallus breakage (Vadas et al. 1976, 1978; Bokn and Lein 1978; Seip et al. 1979).

Mortality at each *Ascophyllum* site is illustrated by plots of the number of remaining tips (Fig. 13) and number of remaining plants (Fig. 14). Means of monthly values from 1979-80 (pre-op) are plotted with their ranges, together with 1986-87 (3-unit operation) data, for the control stations WP and GN. Fox Island *Ascophyllum* mortality data are divided into three periods, corresponding to the temperature regimes specified in the *Ascophyllum* growth section: 1979-84 (FL, pre-op) with means of monthly values plotted with their ranges; 1985-86 (FN, pre-op); and 1986-87 (FN, 3-unit operational). The 1984-85 pre-op data are excluded because of the elimination of *Ascophyllum* at FL in September 1984.

Under 3-unit operational conditions, the control stations had very similar mortality rates, and the experimental station showed a different, higher rate of mortality than the control stations for both tips and plants. Tip mortality was 94% at FN, and 59% and 73% at WP and GN, respectively; plant mortality was 86% at FN, and 40% and 46% at WP and GN (Figs. 13 and 14). Mortality rates at FN were more precipitous than at the control stations, but at all stations, greatest loss in tips and plants occurred in early autumn.

Similar patterns of *Ascophyllum* mortality were evident in pre-op mortality data. The greatest loss of tips and plants was seen at Fox Island, while WP and GN had mortality rates similar to each other under pre-op conditions. Approximate tip and plant losses, respectively, at Fox Island were 80% and 60%, at both WP and GN 75% and 50% (Figs. 13 and 14). Mortality rates at Fox Island were more sudden than at the control stations. Greater mortality is typical of exposed stations, such as FL and FN (cf. Jones and Demetropoulos 1968; Baardseth 1970b; Seip 1980).

Average *Ascophyllum* plant and tip losses in the 3-unit operational period are similar to losses recorded in the pre-op period, excluding 1984-85 data from FL (during and after elimination of *Ascophyllum* at FL). Local plant loss data are similar to those of Chock and Mathieson (1983) who reported 50% of the autumn's *Ascophyllum* standing crop in New Hampshire was lost to storms and ice-rafting. Other researchers have noted extensive losses of *Ascophyllum* axes (e.g., Vadas et al. 1978; Wilce et al. 1978; Topinka et al. 1981; Mathieson et al. 1982) suggesting that decomposition of the fragments provides an important source of nitrogen to the detrital pool.

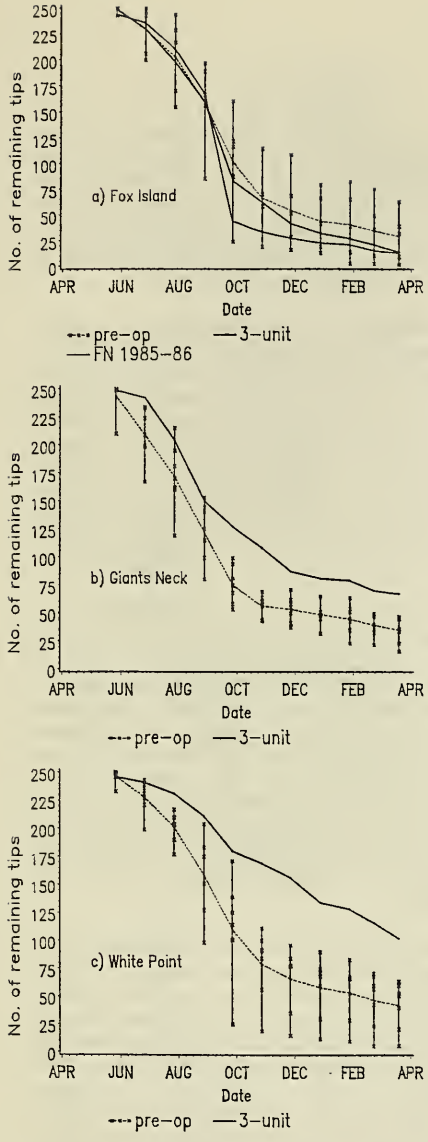

Fig. 13. *Ascophyllum* mortality, as number of remaining tagged tips. Unit 3 operational data (1986-87) are plotted against the mean and range of pre-operational data (1976-86).

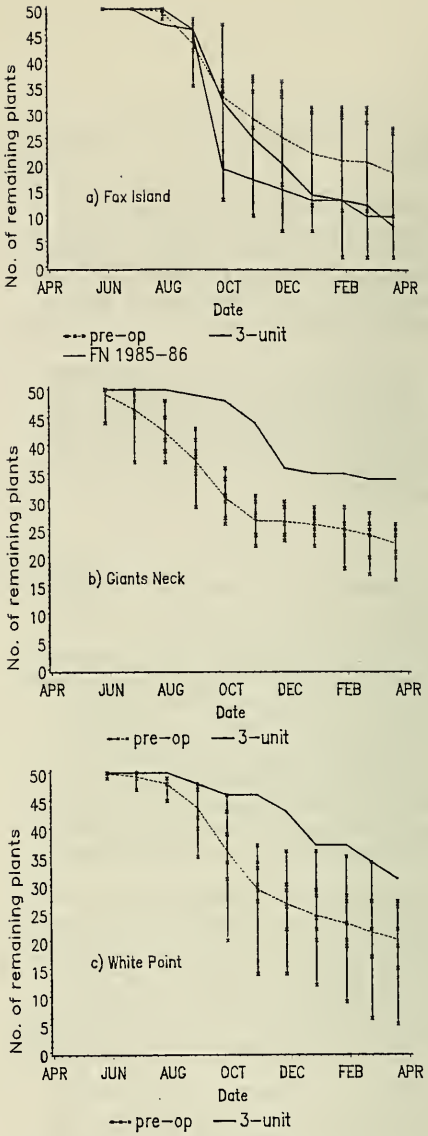

Fig. 14. *Ascophyllum* mortality, as number of remaining tagged plants. Unit 3 operational data (1986-87) are plotted against the mean and range of pre-operational data (1976-86).

Vegetative propagation and lateral proliferation from surviving holdfasts replace lost plant material (Printz 1956; Baardseth 1970a; Keser et al. 1981), and these replacement processes maintain the *Ascophyllum* populations at consistent levels. The effects of thermal stress were seen only at FL, less than one month after the opening of the second quarry cut in August 1983 and in the following summer. Before the second quarry cut was opened, *Ascophyllum* mortality was not associated with proximity to the discharge, but rather to the increased physical stress associated with a higher degree of exposure.

Ascophyllum is not expected to recolonize at FL, even though conditions may be lethal only for a short time in summer. The critical phase for *Ascophyllum* appears to be the establishment and growth of germlings on the substrate (Rueness 1973), and these stages are more susceptible to environmental impact than are adults (Bird and McLachlan 1974). Since repopulation involves long-term survival of individuals, even short-term exposure to lethal water temperatures in summer will prevent *Ascophyllum* recovery. The substratum previously occupied by *Ascophyllum* at FL will continue to be dominated by ephemeral algae, notably *Codium fragile*. The localized scale of this impact (150 m) must be emphasized. Sampling of control populations will continue to provide information to the rocky intertidal monitoring program, as to whether thermal effects may be seen over a larger area (FS, MP, WP), and as to whether trends seen to date will continue during extended 3-unit operation.

Summary

1. Exposure of local rocky shores to the full power 3-unit plume varies with tidal stage as well as distance from the discharges. On an ebbing tide the plume was deflected to the east, across Fox Island, and elevated water temperatures at FL and FE (75 m and 100 m east of the discharges, respectively) for 9-11 hours per tidal cycle. During maximum tidal flooding, temperatures were close to ambient levels for 1-2 hours, as the plume was deflected to the west and the heated water was displaced. About 250 m west of the discharges, at MP, water temperatures were 4 °C above ambient at high tide and 2-3 °C above ambient during low slack water as the plume spread laterally. Consistent full power, full cooling water operation has not existed during periods of maximum ambient water temperature; it is during these conditions that intertidal communities at nearby stations may be affected by the 3-unit thermal plume.

2. Overall, 128 benthic algal species have been identified in the 3-unit operational period. Relative species proportions in the first 12 months of the 3-unit operational period were virtually identical (45:26:29) to those of the pre-operational summary. Spatial and temporal patterns of occurrence were evident in the local intertidal qualitative collections. Community changes at FE (i.e., a decrease in species numbers, shift in divisional proportions, loss of perennial species, and increased abundance and persistence of opportunistic species) were attributed to elevated water temperatures resulting from opening the second quarry cut, not from Unit 3 startup. Most of these community changes have persisted during 3-unit operation, as water temperatures approaching 28 °C have occurred at FE in summer.

3. Local communities, and the factors responsible for structuring them, have remained relatively stable since Unit 3 began operation and were similar to communities under pre-operational conditions. Seasonality, degree of exposure, and competition induced variability in community parameters.

4. Recolonization experiments were undertaken to isolate factors that influence the structure of rocky intertidal communities. Locally, recolonization was influenced by time of year in which denuding occurred and it was related to degree of exposure and intertidal height. After the 1986 autumn denuding, barnacles

recovered after spring barnacle set; *Fucus* also recolonized the following spring.

5. *Ascophyllum* growth rate has been shown to be sensitive to water temperature changes, especially increases to ambient temperature. *Ascophyllum* growth at FN in the 3-unit operational period was similar to that seen in the single pre-op growing season for which there is data (1985-86); growth patterns at the control sites have remained consistent throughout the pre-op and operational periods. Under 3-unit operational conditions, the control sites had very similar mortality rates, and the experimental station showed a different, higher rate of mortality than the control stations for both tips and plants. Local *Ascophyllum* populations have not been affected by operation of Unit 3 to date. Sampling of control populations will continue to provide information as to whether thermal effects may be seen over a larger area, and as to whether trends seen to date will continue during extended 3-unit operation.

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Benthic Infauna

Introduction

Benthic infauna are relatively small organisms inhabiting intertidal beach and subtidal bottom sediments. The many species of worms (polychaetes and oligochaetes), clams (molluscs) and crustaceans (amphipods), which comprise infaunal communities, are important components of marine ecosystems. Many of these organisms are prey species for demersal fishes (Woodin 1982; Moeller et al. 1985; Witman 1985; Le Mao 1986). In Long Island Sound (LIS), annelids are the main food item of winter flounder, *Pseudopleuronectes americanus* (Richards 1963). In addition, many studies have described the influence of infaunal feeding, burrowing and tube building activities on nutrient recycling in marine ecosystems (Goldhaber et al. 1977; Aller 1978; Hylleberg and Maurer 1980; Raine and Patching 1980; Zeitzschel 1980).

Infaunal organisms are also useful environmental monitoring tools because they are relatively sedentary and respond to stress in a predictable manner (Boesch 1973; Reish 1973; Sanders et al. 1980; Boesch and Rosenberg 1982; Young and Young 1982). For example, a physically stressed community will typically exhibit lower numbers of species and high densities of a few characteristic species (e.g., *Polydora ligni*, *Capitella* spp. and *Mediomastus ambiseta*), which are capable of tolerating environmental stress or can rapidly colonize an area following disturbance (McCall 1977; Reish et al. 1980; Sanders et al. 1980).

Impact studies based on observed changes in infaunal community abundance and species composition assume that the structure of the unimpacted community can be described, and that any trends evident before impacts occur can be identified and removed (Nichols 1985). Because naturally occurring variations in physical factors such as cold winters (Beukema 1979), storms (Boesch et al. 1976), heavy rainfall (Flint 1985; Jordan and Sutton 1985) or changes in the level of competition and predation (Levinton and Stewart 1982; Woodin 1982; Moeller et al. 1985) can strongly affect infaunal communities, only long-term data can adequately describe the range and overall trends in community abundance and composition required for impact assessment studies (Holland 1985).

Benthic infaunal communities in the vicinity of Millstone Nuclear Power Station (MNPS) have been sampled since 1969, as part of a larger monitoring program designed to assess the potential impacts of construction and operation of Millstone Units 1 and 2. Plant-related changes in benthic communities during this period have been attributed to construction and opening of the Unit 3 discharge cut and to construction and dredging near the intake structures (NUSCO 1987). These data also provide the baseline conditions against which potential changes associated with Unit 3 start-up will be evaluated (NUSCO 1987).

This is the first report to include data collected after commercial start-up of Millstone Unit 3 (April 1986). Environmental changes, which could possibly impact infaunal communities, include doubling of the heated effluent discharged into LIS and the enlargement of the area subjected to the scour produced by the additional intake and discharge of the 3-unit (combined) cooling waters. In addition, changes might occur in response to chemical additions associated with the increased volume produced during 3-unit operations. To assess changes in local benthic communities that might occur during 3-unit operation at MNPS, the infaunal sampling program was designed to address the following objectives:

1. characterize the abundance and species composition of infaunal communities inhabiting shallow subtidal and intertidal areas both within and beyond the influences of 3-unit operation at MNPS,

2. describe spatial and temporal patterns in these communities and identify the extent and direction of changes attributable to 3-unit operation and

3. assess the ecological significance of power plant-induced changes should they occur.

For the purpose of assessing 3-unit operational impacts, the pre-operational period was considered to extend from March 1979 - June 1985. Collections made from September 1985 - June 1986 and from September 1986 - June 1987 (the 1986 and 1987 reporting years, respectively) will be considered operational years. The 1986 sampling year included three sampling periods before commercial start-up; however, this was considered an operational year because certain conditions (i.e., operation of Unit 3 cooling water pumps), which could influence infaunal communities, existed during at least 2 of the 4 quarters considered the 1986 sampling year.

Materials and Methods

Infaunal communities were sampled at four subtidal and three intertidal stations (Fig. 1). The Giants Neck subtidal (GN-S) and intertidal (GN-I) stations are located 5.5 km west of the power plant and serve as reference stations because both are beyond any physical influences of the power plant discharge. Data collected at these stations provide the baseline for assessment of naturally-induced changes which might occur on a regional scale (e.g., hurricanes, severe winters, heavy precipitation). The intake subtidal station (IN-S) is located 0.1 km seaward of the Millstone Unit 2 and Unit 3 intake structures and is exposed to the scouring (if any) produced by intake of cooling water. The effluent subtidal station (EF-S) is located approximately 0.1 km offshore of the Unit 3 discharge. This area is subjected to plant-induced changes related to temperature, scour, and possible chemical additions associated with power plant operations. The Jordan Cove subtidal (JC-S) and intertidal (JC-I) stations, located 0.5 km east of the power plant and the White Point (WP-I) intertidal station, 1.6 km east of the power plant, are all within the area influenced by the thermal plume during some tidal stages (see Hydrothermal Studies section of this report).

At each subtidal and intertidal station, ten 0.0078 m^2 cores (10 cm diameter x 5 cm deep) were collected quarterly (September, December, March and June). For reporting purposes, a sampling year begins in September and ends in June with the year of the June sample assigned as the sampling year. Subtidal samples were taken within 3 m of each station marker by SCUBA divers. Each sample was placed in a 0.333 mm mesh Nitex bag and brought to the surface. Intertidal samples were collected at approximately 0.5 m intervals parallel to the water line at mean low water.

Samples were brought to the laboratory and fixed with a 10% buffered formalin/rose bengal solution. After a minimum of 48 h, organisms were floated from the sediments onto a 0.5 mm mesh sieve and the float and residue were preserved separately in 70% ethyl alcohol. Organisms were removed under dissecting microscopes, sorted into major groups (annelids, arthropods, molluscs, and others), identified to the lowest possible taxon and counted. Organisms that were too small or otherwise not quantitatively sampled by our methods (e.g., nematodes, ostracods, copepods, and foraminifera), were not removed from samples.

At the time of infaunal sampling, a 3.5 cm diameter x 5 cm deep core was taken for sediment analysis which was performed using the dry sieving method (Folk 1974).

Data Analyses

Impacts on infaunal communities attributable to start-up of Millstone Unit 3 and the subsequent operation of 3 units at MNPS were assessed by

Fig. 1. Map of the Millstone Point area showing the location of intertidal (GNI = Giants Neck, JCI = Jordan Cove and WPI = White Point) and subtidal (GNS = Giants Neck, INS = Intake, EFS = Effluent, JCS = Jordan Cove) infaunal monitoring stations.

comparing data obtained during the pre-operational and operational periods. Power-plant related impacts should be evidenced as changes in infaunal abundance, species number, and changes in dominance structure (Boesch 1973; Oden 1979; Jordan and Sutton 1985). In addition, impacts might result in high densities of species considered "opportunists". (McCall 1977; Sanders et al. 1980). However, in LIS, many of these species are considered typical of soft-bottom communities (Rhoads and Young 1970; McCall 1977), thus, their appearance may not necessarily reflect power plant-induced impacts. The data analysis techniques used in this report were selected to allow for identification of power plant impacts within the naturally variable framework characteristic of temperate intertidal and shallow-water macrobenthic communities (Eagle 1975; Livingston 1982; Flint and Younk 1983; Holland and Mountford 1977).

Regression Analyses

Multiple regression techniques were used to identify and remove significant temporal variation in community abundance, numbers of species and

dominant species abundance related to abiotic factors, reproductive/recruitment cycles, and long-term climatic conditions. Removal of this variation was performed to improve the sensitivity of statistical analyses used to compare data collected during the pre-operational and operational periods. Regression analysis techniques were applied to log-transformed (LN(X + 1)) quarterly abundances (no./core for total community and population abundances) and quarterly mean numbers of species (no./core) collected from March 1979 through June 1987.

The following factors were used as explanatory variables:

Precipitation

Daily precipitation records compiled by the U.S Weather Bureau at the Groton Filtration Plant were obtained from June 1976 through June 1987. Values to the nearest 0.01 inch were used as our "rain" data for the regression model.

Water and Air Temperature

Ambient water temperatures (at the intake structures) and air temperatures (at the 33-foot level of the Millstone meteorological tower) were obtained from the Northeast Utilities Environmental Data Acquisition Network (EDAN). Daily averages, based on observations made at 15-minute intervals, were calculated for the period June 1976 to June 1987.

Wind Speed and Direction

Wind speed and direction (at the 33-foot level of the Millstone meteorological tower) were extracted from the EDAN database at 15-minute intervals from June 1976 to June 1987. These values were used to calculate a Wind Index which was wind speed weighted according to wind direction. A NOAA navigational chart of the sampling area was used to calculate site-specific, wind directional weighting coefficients. The directional weight ranged from 0, when wind could not influence the station, to 1, when the wind could result in waves directly affecting the area. The Wind Index was then computed by multiplying the directional weight by the wind speed. Because the effect of wind was assumed to be cumulative, daily averages were derived using only Wind Index values greater than 0 (that is, when the wind was from a direction which could produce wind effects).

Sedimentary Parameters

Sedimentary parameters including mean grain size and silt/clay content were obtained as part of the monitoring studies and the quarterly values included as explanatory variables in the regression analyses.

Seasonal Reproduction-Recruitment Component

Infaunal organisms in the Millstone area exhibit annual peaks in abundance, which often reflect the seasonal nature of reproduction and recruitment cycles or periods of favorable climatic conditions. Spectral analyses of quarterly data showed that annual cycles in community abundance and numbers of species were present. To account for this periodicity, harmonic terms having a period of 1 year were included as explanatory variables in the regression models.

Climatic Extremes (Deviations)

Additional variables were created to represent periods of extreme climatic conditions which have occurred during the sampling period. High or low deviations (i.e., extremes) were derived for each abiotic factor as the difference between the quarterly mean or daily value and the 11 year mean for that quarter. Deviations based on quarterly means reflected the effects of longer term extremes (e.g., an unusually cold winter), while those based on daily values were intended to remove the effects of shorter-term episodic events (e.g., storms). Daily deviations were averaged and summed (for cumulative effects) over each sampling quarter.

In all, 32 variables were used during initial multiple regression analyses. These included 2 sedimentary parameters, 2 seasonal/reproductive components and 7 climatic variables, each of which had 4 values representing daily and quarterly high and low extremes.

Model Selection Procedure

The quarterly mean values were first detrended using a polynomial regression equation to create the residuals needed for regression analysis. If no significant long-term trend was evident, residuals were created by subtracting the quarterly mean from the 11 year mean. A step-wise multiple regression was then used on these residuals to select explanatory abiotic variables and combinations of variables that were significantly different from zero, at a probability level of $p < 0.05$. This probability was deemed sufficient to guard against fitting more parameters than can be reliably estimated, given the sample size. The model that minimized the mean square error and maximized the R^2 was selected as best model describing observed variability in community abundance, numbers of species and abundances of selected species.

Analyses of covariance were then conducted to test for annual differences in abundance and species numbers using significant explanatory variables as covariates. Results of these analyses and pair-wise t-tests on adjusted means (least square means) were used to identify significant ($p < 0.05$) interannual differences in the abundance and species number. In this report, pair-wise differences among years involving only 1986 and 1987 will be emphasized.

Biological Index Value

The Biological Index Value (BIV) of McCloskey (1970), an index of dominance, was calculated for the 10 most abundant taxa at each station collected from 1986-1987. To provide comparisons with the pre-operational data, a BIV was also calculated for 1980-85. To calculate the BIV, the top ten numerically abundant species in each sampling year are ranked from highest to lowest and ranks summed for each year. The BIV is sum of the ranks across all years for each taxon expressed as a percentage of a theoretical maximum sum that occurs if a species ranked first in all sampling years. For example, the BIV would be equal to 100% and the theoretical maximum equal to 60 when a species ranks first in abundance in each of six years and a total of 10 species are collected.

Species Diversity

Species diversity at each station was calculated using the Shannon information index:

$$H' = \sum_{i=1}^{S} \frac{n_i}{n} \log_2 \frac{n_i}{N} \quad (\textit{Pielou } 1977)$$

where n_i = number of individuals of the i^{th} species, N = total number of individuals for all species and S = number of species. An evenness component of diversity was calculated as:

$$J = \frac{H'}{H_{max}} \quad (\textit{Pielou } 1977)$$

where $H_{max} = \log_2 S$ and represents the theoretical maximum diversity when all species are equally abundant. Evenness ranges from zero to one and increases as the numbers of individuals among species become more evenly distributed. Diversity calculations excluded oligochaetes and rhynchocoels (groups that sometimes accounted for over 80% of the total organisms collected) because they were not identified to species. Similarly, other organisms that could not be identified to species, either because they were juveniles or in poor physical condition, were excluded from this analysis.

Numerical Classification and Cluster Analyses

Cluster analyses, based on annual abundances of organisms, were performed using the Bray-Curtis similarity coefficient. This coefficient is cal-

culated using the formula:

$$S_{jk} = \frac{\sum_i 2\min(X_{ij}, X_{ik})}{\sum_i (X_{ij} + X_{ik})} \quad \textit{(Clifford and Stevenson 1975)}$$

where X_{ij} = abundance of attribute i at entity j and X_{ik} = abundance of attribute i at entity k. Based on these similarities, cluster analyses incorporating a flexible sorting strategy ($\beta = -0.25$) was used to form station groups (Lance and Williams 1967).

Intertidal Results

Sedimentary Environment

Intertidal beach sediments at GN during the 1986-87 operational period were comprised of medium sands (0.3 - 0.4 mm) which consistently contained low amounts (< 1%) of silt/clay (Fig. 2). At JC, grain size in 1986-87 ranged from 0.5 - 1.0 mm (coarse-very coarse) and silt/clay content from 0.5 - 3.3% . Medium sands also predominated during this period at WP ranging from 0.4 - 0.8 mm; silt/clay content at this station was also low throughout the sampling period (< 1%).

In the operational period, sediments were generally coarser at both potentially impacted stations (JC and WP) than during pre-operational years. Higher grain size was first observed in June 1985, prior to any possible 3-unit environmental changes that might influence grain size at our stations. Sedimentary characteristics at GN from 1986-87 were consistent with previous years results, and with no discernable increase over 1986-87 comparable to that observed at JC and WP.

General Community Composition

Intertidal infaunal communities during 1986 and 1987 were dominated by oligochaetes at JC (68% and 87%), rhynchocoels at WP (68% and 59%) and polychaetes (70% and 60%) at GN, respectively (Table 1). Polychaetes were the second most abundant group, contributing 12-32% of the fauna at JC and 26-34% at WP. Oligochaetes accounted for only 5-6% of the total at WP and rhynchocoels < 1% of the total collected at JC. At GN, oligochaetes were the second most abundant group (21%) followed by rhynchocoels (8-9%).

Polychaetes generally accounted for over half of the total species collected each year. Arthropod species were nearly as numerous at JC as polychaetes, although abundances of individuals were usually low. Other major groups at this station (e.g., molluscs, rhynchocoels) were represented by few species. At both WP and GN, numbers of mollusc and arthropod species were low in 1986 and 1987.

The general community composition at JC during the 1986-87 operational period was typical of that observed during the pre-operational study. Oligochaetes dominated this community and accounted for over 80% of the total organisms; polychaetes were usually the second most abundant group and accounted for most of the species. At WP, total abundances of polychaetes in 1986 and 1987 were below the 1980-85 range; the number of oligochaetes at this station was also low while that of rhynchocoels was near the high end

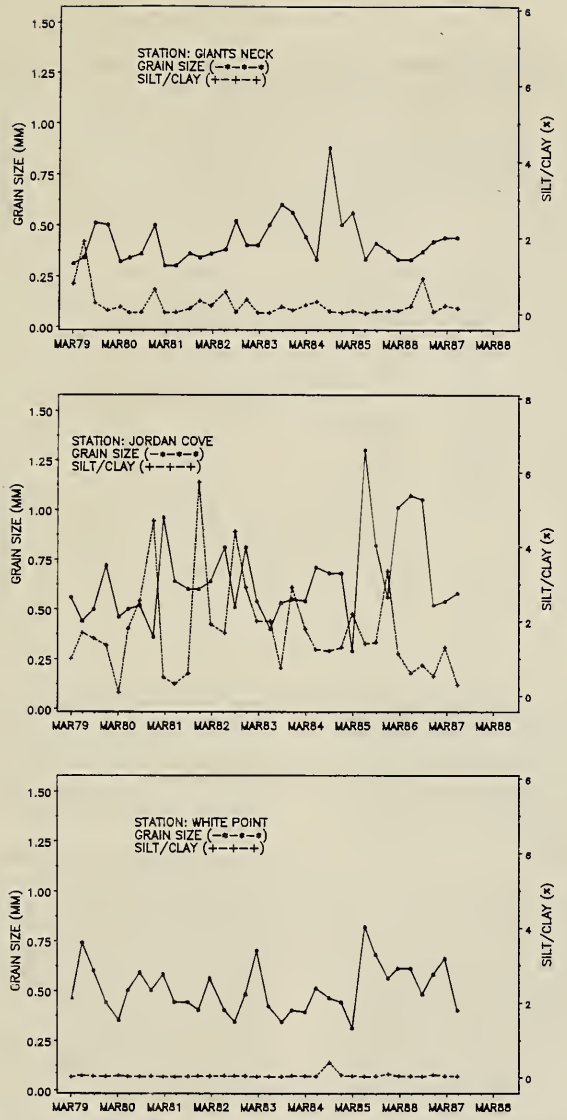


Fig. 2. Quarterly mean grain size (mm) and silt/clay content (%) of sediments sampled at Millstone intertidal stations from March 1979 - June 1987.

TABLE 1. Number of species (S), number of individuals (N) and percentage of the total (%) for each major taxon collected at Millstone intertidal stations September 1985 - June 1987, with ranges from 1980 -1985.

STATION	Range 1980-1985			1986			1987		
	S	N	%	S	N	%	S	N	%
GIANTS NECK									
Polychaeta	13-24	613-2222	40-82	16	1040	70	27	1408	60
Oligochaeta	-	79-626	4-40	-	306	21	-	486	21
Mollusca	0-8	0-14	0-11	1	1	< 1	4	8	< 1
Arthropoda	5-14	12-59	< 1-2	3	3	< 1	3	19	1
Rhynchocoela	-	109-932	7-31	-	131	8	-	210	9
JORDAN COVE									
Polychaeta	12-22	1055-4120	12-30	23	3551	32	19	1651	12
Oligochaeta	-	86-15012	40-86	-	7809	68	-	12365	87
Mollusca	6-10	10-711	< 1-5	5	40	< 1	7	35	< 1
Arthropoda	12-24	55-968	< 1-14	13	77	< 1	15	50	< 1
Rhynchocoela	-	1-70	< 1-1	-	92	< 1	-	80	< 1
WHITE POINT									
Polychaeta	12-22	428-1548	44-60	9	236	26	13	391	34
Oligochaeta	-	59-669	4-31	-	46	5	-	72	6
Mollusca	1-6	1-18	< 1-1	2	3	< 1	1	1	< 1
Arthropoda	0-7	2-11	< 1-1	6	9	1	4	8	< 1
Rhynchocoela	-	273-783	13-40	-	620	68	-	692	59

of the range. Thus at WP, the overall contribution of rhynchocoels increased, accounting for 59-68% of the total organisms in 1986-87 versus a maximum of 40% during the pre-operational period. In 1986-87, polychaetes continued to be the major component at GN, and there were no major changes relative to 1980-85.

Community Abundance

Quarterly mean abundance with multiple regression predictions, and adjusted annual mean abundances of the three intertidal communities are plotted in Figures 3 and 4, respectively. Abundance (exponentials of values in Figure 3) during 1986-87 ranged from 4 - 95/core at GN, 23 - 701/core at JC and from 3 - 62/core at WP. In both 1986 and 1987, strong seasonal peaks were evident at JC and WP in June, while at GN densities peaked in either June or September. When compared to previous years, abundances at JC during 1986-87 were within the range observed in past years. At WP, 4 of the 8 quarterly means obtained since September 1985 were at or below the extremes observed during 1980-85.

The multiple regression analyses indicated that there have been no increasing or decreasing trends in community abundance at any of the intertidal stations since 1980. In addition, comparisons of annual means (t-tests) revealed few significant differences among comparisons involving 1986 or 1987. The 1986 abundance at JC was significantly different from only 1982, while 1986 at WP was significant from 1980 and 1984. At GN, 1986 and 1987 abundances were not significantly different from any of the previous years.

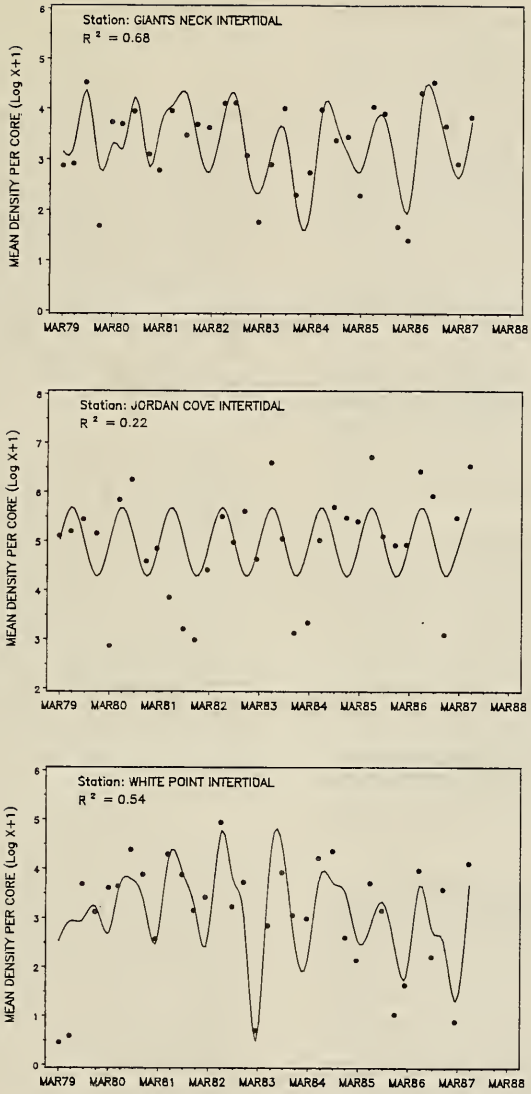

Station: GIANTS NECK INTERTIDAL
R ² = 0.68
MEAN DENSITY PER CORE (Log X+1)
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88
Station: JORDAN COVE INTERTIDAL
R ² = 0.22
MEAN DENSITY PER CORE (Log X+1)
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88
Station: WHITE POINT INTERTIDAL
R ² = 0.54
MEAN DENSITY PER CORE (Log X+1)
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88

Fig. 3. Quarterly means of log-transformed abundance ((LN(X + 1)) and multiple regression predictions of Millstone intertidal infaunal communities from March 1979 - June 1987.

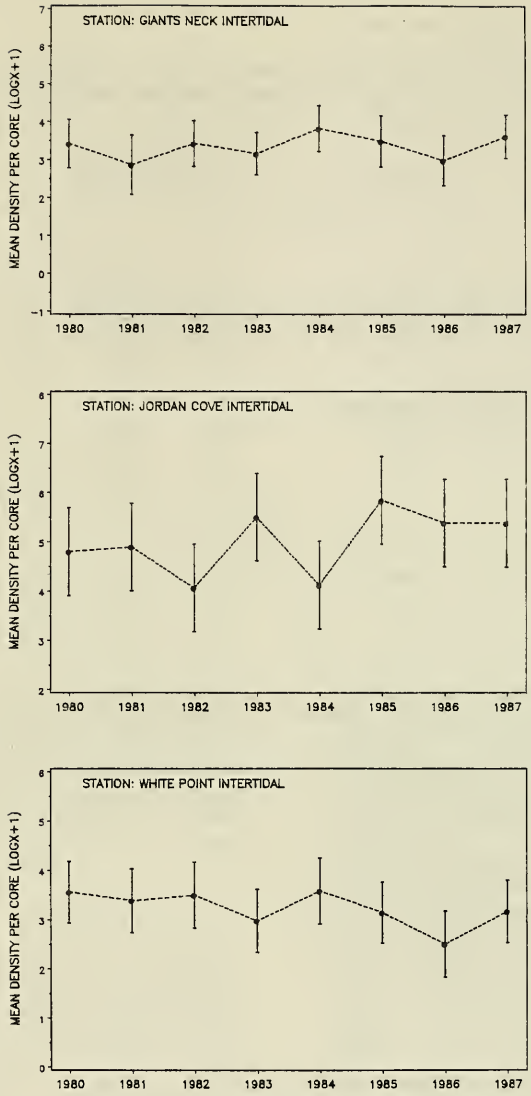


Fig. 4. Annual means of log-transformed abundance ((LN(X + 1)) of Millstone intertidal infaunal communities from March 1979 - June 1987. (Annual means were adjusted using analysis of covariance which included abiotic and climatic conditions as covariates. Error bars represent ±2 SE.)

Number of Species

The number of species ranged from 2 - 9/core at GN, 4 - 12/core at JC and from 1 - 6/core at WP during 1986-87 (Fig. 5). Highest numbers were more frequently found at JC, while values at GN and WP more were similar to each other. At all stations, species number generally mirrored community abundance. An exception to this was June 1987, a period of low species numbers but high density (due to oligochaetes). The number of species collected at WP was generally low during 1986-87 and 4 of 8 values obtained since September 1985 were near the lower end of the range established since 1980.

The multiple regression analysis removed 48%, 74% and 47% of the variation in species number from 1980-87 at GN, JC and WP, respectively. After removing this variation, there were no trends in species numbers at any of the intertidal stations (Fig. 6). Year-to-year comparisons (t-tests) indicated that species numbers at GN in 1987 were significantly higher than in 1986, but neither year was significantly different from those before 1985. At JC, the 1986 value was significantly higher than only 1982 and at WP, 1986 was significantly lower than 1980, 1981 and 1984. Number of species at this station in 1987 was not significantly different from any previous year.

Community Dominance

Oligochaetes dominated the macrofaunal community at JC, averaging 195/core and 309/core in 1986 and 1987, respectively (Table 2.). This taxon was also the most abundant organism in each of 1980-85 sampling years as reflected by the high BIV (100%). *Scolecolepides viridis* (15 - 35/core) and *Hediste diversicolor* (20 - 29/core) were the next most abundant taxa at JC during the operational period. These species also had high BIV's during the pre-operational and operational sampling periods. *Capitella* spp. and *Polydora ligni* ranked 5th and 6th in 1986-87 and although they occurred in much lower abundance than the top three taxa, they have generally ranked similarly among the dominants in past years.

At WP, rhynchocoels, *Paraonis fulgens*, *Haploscoloplos fragilis* and oligochaetes numerically dominated during the 1986-87 period and were also dominant during the previous 5 years. Rhynchocoels were more abundant in the last two sampling years (16 - 17/core) than during the pre-operational period (13/core). This taxon was the most consistently dominant organism (high BIV's) during both the pre-operational and operational sampling periods. Other dominant species at WP during 1986-87 were collected in lower densities than 1980-85, although most were within range of previous years. Except for *Streptosyllis arenae*, the position of these species among the dominants was similar to that observed during the pre-operational period.

Five taxa (oligochaetes, *Haploscoloplos fragilis*, *Scolecolepides viridis*, *Paraonis fulgens* and rhynchocoels) dominated the GN community. These species were also the predominant organisms during the 1980-85 sampling period, although the rank order differed. Relative to the pre-operational period, rhynchocoel abundance in 1986 and 1987 was generally low as shown by their lower position among the dominants. Other than rhynchocoels, dominant taxa were found in abundances that were generally higher than the average over previous years, although their rank among the dominants was similar.

At all stations, there were some changes in the organisms that occurred among the ten numerical dominants during 1986-87 when compared to the previous 5 years. Additions or deletions typically involved taxa that exhibited large fluctuations from year to year and thus had low BIV's. During the operational period, four species at JC and WP, and two at GN were among the top ten for the first time. At JC, *Fabrica sabella* was collected in high densities (10/core) in 1986. At WP and GN, species among the top ten for the first time in 1986-87, were rare (< 1/core).

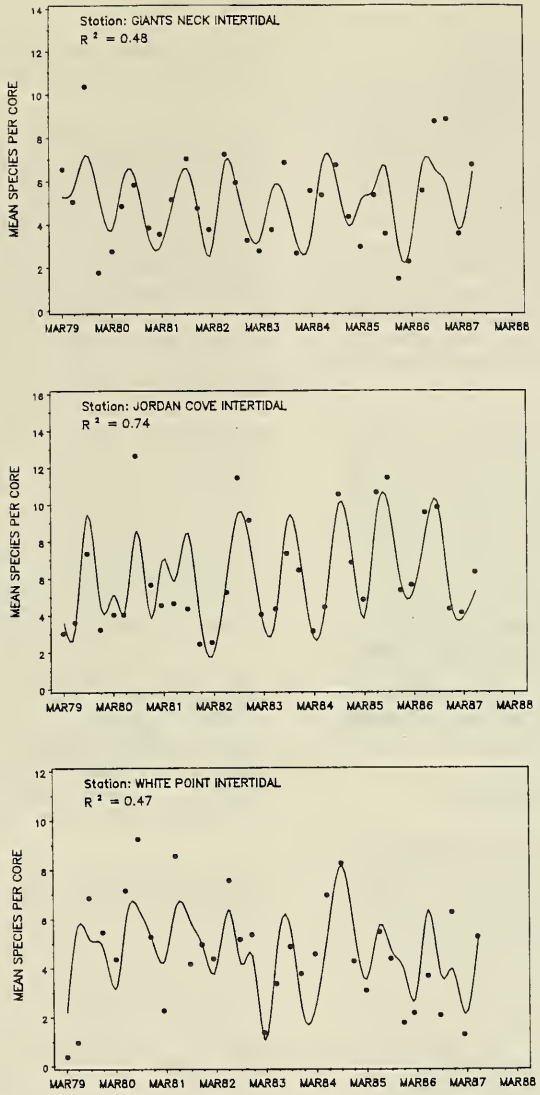

Station: GIANTS NECK INTERTIDAL
R ² = 0.48
MEAN SPECIES PER CORE
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88
Station: JORDAN COVE INTERTIDAL
R ² = 0.74
MEAN SPECIES PER CORE
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88
Station: WHITE POINT INTERTIDAL
R ² = 0.47
MEAN SPECIES PER CORE
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88

Fig. 5. Quarterly means of number of species and multiple regression predictions of Millstone intertidal infaunal communities from March 1979 - June 1987.

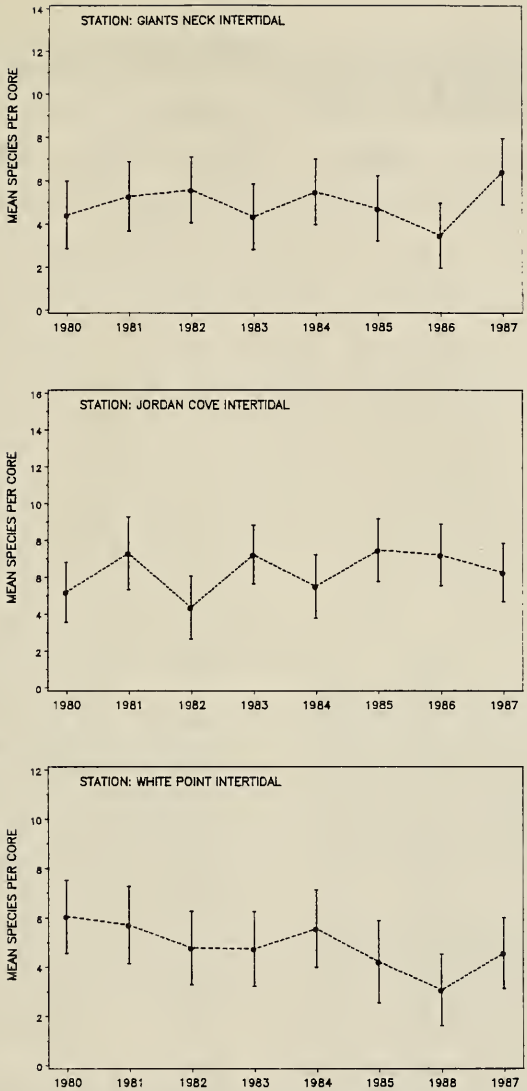


Fig. 6. Annual means of number of species of Millstone intertidal infaunal communities from March 1979 - June 1987. (Annual means were adjusted using analysis of covariance which included abiotic and climatic conditions as covariates). Error bars represent ±2 SE.

TABLE 2. Mean number of individuals per core and Biological Index Value (BIV) of the ten most numerically abundant taxa collected at the Millstone intertidal stations September 1985 - June 1987, with annual range and mean (no./core) for 1980-1985.

	1980-85		1986	1987	1980-85	1986-87
Station	Range	Mean	Mean	Mean	BIV	BIV
GIANTS NECK						
Oligochaeta	2-16	6	8	12	83.3	91.7
Haploscoloplos fragilis	4-9	5	7	10	89.2	83.3
Scolecolepides viridis	2-11	7	17	5	85.3	83.3
Paraonis fulgens	1-19	8	1	16	84.3	79.2
Rhynchocoela	3-15	8	3	5	90.2	75.0
Capitella spp.	< 1-5	3	< 1	1	75.5	52.1
Hediste diversicolor	< 1-2	1	1	< 1	53.9	52.1
Polydora ligni	0- < 1	1	< 1	1	52.9	41.7
Mediomastus ambiseta	0- < 1	< 1	< 1	1	-	29.2
Schistomeringos caecus	0- < 1	< 1	< 1	< 1	-	29.2
Pygospio elegans	0- < 1	< 1	< 1	< 1	27.9	27.1
Neohaustorius biarticulatus	0- < 1	< 1	0	< 1	32.8	16.7
Microphthalmus sczelkowii	< 1- < 1	< 1	0	< 1	47.1	-
Tharyx acutus	0- < 1	< 1	0	0	36.8	-
Gammarus lawrencianus	< 1- < 1	< 1	0	0	35.8	-
Streptosyllis arenae	0- < 1	< 1	< 1	< 1	32.9	-
Haustorius canadiensis	0- < 1	< 1	0	0	31.9	-
Lepidonotus squamatus	0- < 1	< 1	0	0	20.6	-
Polydora socialis	0- < 1	< 1	0	0	19.6	-
JORDAN COVE						
Oligochaeta	40-375	185	195	309	100.0	100.0
Scolecolepides viridis	14-32	21	35	15	94.4	88.5
Hediste diversicolor	2-46	15	29	20	88.1	88.5
Capitella spp.	< 1-9	4	4	3	77.0	69.2
Polydora ligni	< 1-8	3	3	2	77.1	57.7
Rhynchocoela	< 1-1	< 1	2	2	60.1	57.7
Streptosyllis arenae	0- < 1	< 1	5	< 1	-	46.1
Fabricia sabella	0- < 1	< 1	10	< 1	-	42.3
Mya arenaria	0-1	< 1	1	< 1	-	36.5
Streblospio benedicti	< 1-2	< 1	1	< 1	52.4	30.8
Neanthes acuminata	0	0	0	< 1	-	28.8
Gemma gemma	< 1-10	3	< 1	< 1	68.3	26.9
Gammarus lawrencianus	< 1-12	< 1	3	< 1	65.1	26.9
Gammarus mucronatus	< 1-1	< 1	< 1	0	53.2	-
Microphthalmus sczelkowii	0-1	< 1	< 1	< 1	44.0	-
Lacuna vincta	< 1- < 1	< 1	< 1	< 1	41.3	-
Pygospio elegans	0-1	< 1	< 1	< 1	40.9	-
Nereis succinea	0-1	< 1	< 1	0	38.9	-
Leptocheirus pinguis	0- < 1	< 1	0	< 1	35.3	-
Eteone heteropoda	0- < 1	< 1	< 1	< 1	34.9	-
Crepidula plana	0- < 1	< 1	0	< 1	31.1	-
Edotea triloba	0-1	< 1	< 1	< 1	31.0	-
Phoxocephalus holbolli	0- < 1	< 1	0	0	22.2	-
Eteone longa	0- < 1	< 1	0	< 1	21.8	-
Potamilla reniformis	0- < 1	< 1	0	0	21.8	-

- = not among the ten most numerically abundant taxa

TABLE 2. cont'd

Station	1980-85 Range	1980-85 Mean	1986 Mean	1987 Mean	1980-85 BIV	1986-87 BIV
WHITE POINT						
Rhynchocoela	7-20	13	16	17	95.6	100.0
Paraonis fulgens	2-22	8	4	4	89.5	92.3
Haploscoloplos fragilis	4-12	8	1	3	92.1	84.6
Oligochaeta	1-17	7	1	2	88.2	76.9
Scolecolepides viridis	< 1-4	1	1	< 1	60.1	59.6
Parapionosyllis longicirrata	< 1- < 1	< 1	< 1	1	53.1	50.0
Streptosyllis arenae	1-4	2	< 1	1	77.2	46.1
Philoscia vittata	0-0	0	< 1	0	-	38.5
Capitella spp.	< 1-3	1	< 1	< 1	66.7	32.7
Gemma gemma	0-0	0	< 1	0	-	32.7
Microdeutopus gryllotalpa	0-0	0	< 1	0	-	32.7
Scolelepis squamata	0- < 1	< 1	0	< 1	-	30.7
Polydora ligni	0- < 1	< 1	0	< 1	45.6	23.1
Exogone hebes	< 1- < 1	< 1	< 1	< 1	46.1	-
Pygospio elegans	0-1	< 1	0	0	42.1	-
Hediste diversicolor	0- < 1	< 1	0	< 1	38.6	-
Aricidea catherinae	0-2	< 1	< 1	0	37.3	-
Mytilus edulis	0- < 1	< 1	0	< 1	33.3	-
Archiannelida	0- < 1	< 1	0	0	32.9	-
Magelona rosea	0- < 1	< 1	0	0	27.6	-
Sphaerosyllis erinaceus	0- < 1	< 1	0	0	25.4	-
Lacuna vincta	0- < 1	< 1	0	0	24.1	-
Polydora socialis	0- < 1	< 1	0	0	24.1	-

- = not among the ten most numerically abundant taxa

Dominant Taxa

In the following section, temporal patterns in abundance of dominant intertidal taxa were examined using the same multiple regression analysis procedure used to remove natural sources of variation in community density and numbers of species. Taxa were selected if they ranked among the dominants (BIV's > 80%) during either the pre-operational or the operational period. Quarterly mean abundances are presented with multiple regression models and adjusted annual means. Values presented in the following figures are log transformed (LN(X + 1)) and those in the text are the exponentials of these values.

Oligochaetes

These deposit-feeding annelids commonly inhabit the littoral and shallow subtidal marine habitats in areas of high organic content and feed on the bacterial populations that colonize organic detritus (Soulsby et al. 1982; Hull 1987). In the Millstone area, oligochaetes have been among the more dominant intertidal organisms. This group ranked first in abundance at JC in both the pre-operational and operational periods. Although oligochaetes were consistently among the dominants at WP and GN, average densities were frequently an order of magnitude less than those at JC.

Quarterly oligochaete abundance from September 1985 - June 1987, ranged from 0 - 30/core at GN, 9 - 666/core at JC, 1 - 3/core at WP (Fig. 7A-C). Densities at JC varied widely during the last two years and values near the upper and lower extremes were obtained. Seasonal peaks occurred in June of 1986 and 1987. Large seasonal fluctuations also occurred at GN during the 1986-87 period, but unlike JC, peaks occurred in September. The oligochaete population at WP

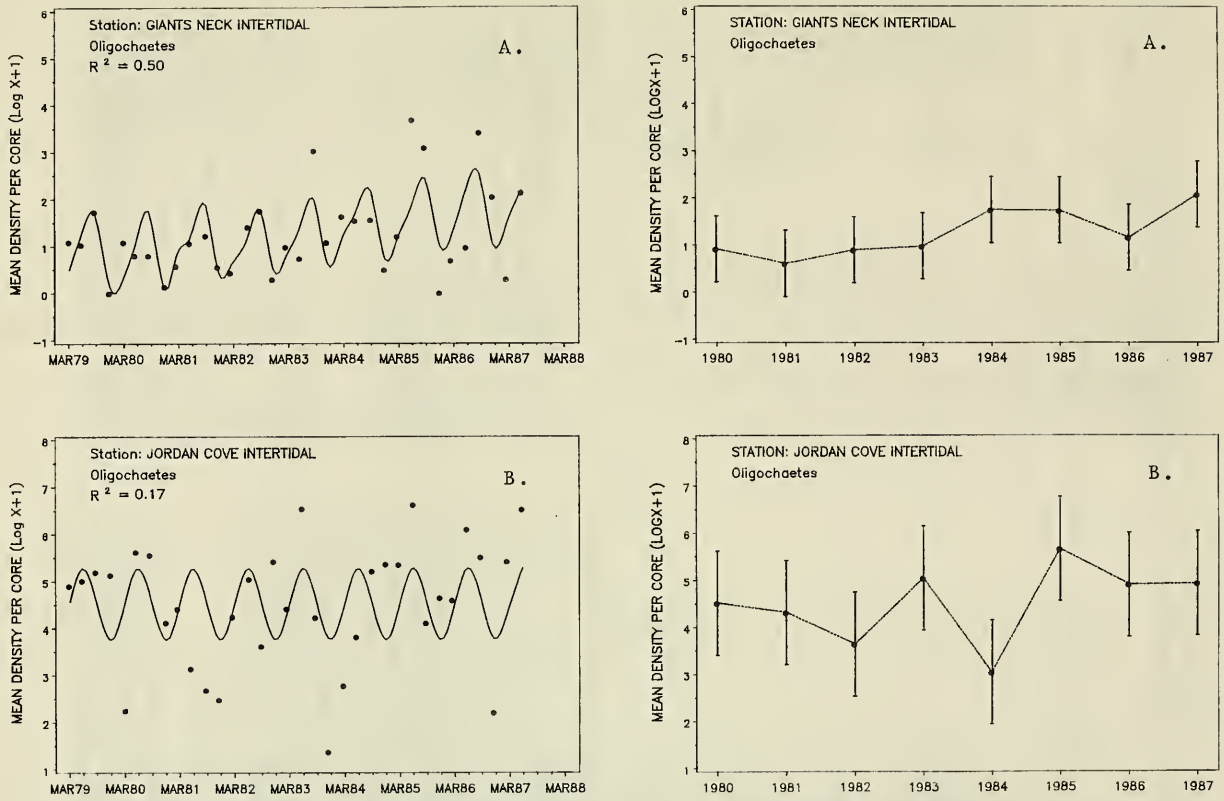

Station: GIANTS NECK INTERTIDAL
Oligochaetes
R ² = 0.50
A.
MEAN DENSITY PER CORE (Log X+1)
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88
STATION: GIANTS NECK INTERTIDAL
Oligochaetes
A.
MEAN DENSITY PER CORE (LOGX+1)
1980 1981 1982 1983 1984 1985 1986 1987
Station: JORDAN COVE INTERTIDAL
Oligochaetes
R ² = 0.17
B.
MEAN DENSITY PER CORE (Log X+1)
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88
STATION: JORDAN COVE INTERTIDAL
Oligochaetes
B.
MEAN DENSITY PER CORE (LOGX+1)
1980 1981 1982 1983 1984 1985 1986 1987

Fig. 7. Quarterly means of log-transformed abundance ((LN(X + 1)), multiple regression predictions, and adjusted annual abundances of Millstone intertidal infaunal communities from March 1979 - June 1987. (Annual means were adjusted using analysis of covariance which included abiotic and climatic conditions as covariates. Error bars represent ± 2 SE.)

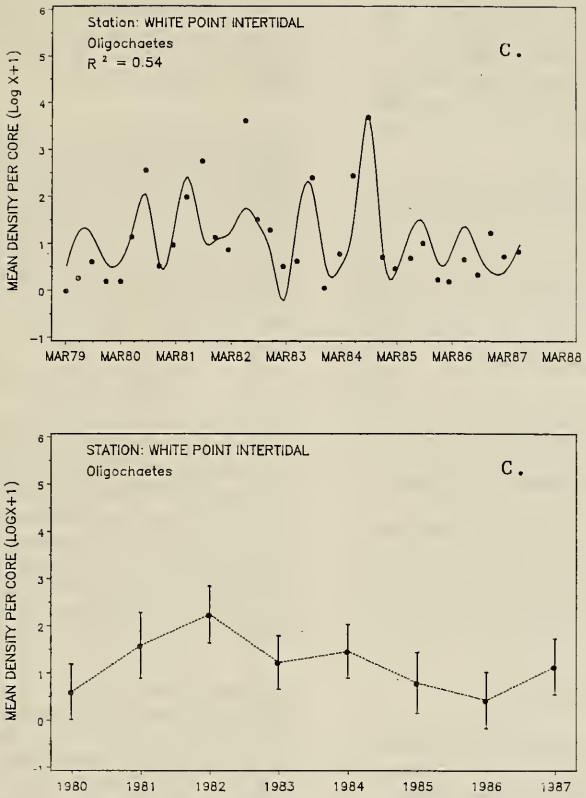

Station: WHITE POINT INTERTIDAL
Oligochaetes
R 2 = 0.54
C.
MEAN DENSITY PER CORE (Log X+1)
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88
STATION: WHITE POINT INTERTIDAL
Oligochaetes
C.
MEAN DENSITY PER CORE (LOGX+1)
1980 1981 1982 1983 1984 1985 1986 1987

Fig. 7. Continued.

during the last two years was much less variable than at other stations.

After multiple regression analysis removed 50% (GN), 17% (JC) and 54% (WP) of the temporal variation, no significant trends were evident at JC or GN, while at WP, there was a significant decreasing trend from 1982-1985 that continued through the operational period (1986-87). Oligochaete abundance at GN in 1987 was significantly higher than abundances in 1980-1983. At JC, annual means for 1986 and 1987 (also 1985) were higher than most previous years, but significant from only 1984. Mean abundance at WP in 1986 and 1987 was significantly lower than only 1982, when a peak in abundance occurred.

Scolecolepides viridis

Scolecolepides viridis is most common intertidally, burrows in a variety of substrata and is particularly abundant in sand (Wells and Gray 1964). This polychaete is most frequently found in areas of reduced salinity (Smith 1964). Adults

inhabit a mucus-lined burrow and feed on surface deposits, detritus, diatoms, filamentous algae and nematodes (Sanders et al. 1962). At Millstone, this species consistently ranked among the numerical dominants at GN and JC and although frequently among the top ten at WP, abundances at this station were usually very low (< 1/core).

During 1986-87, quarterly densities of *Scolecolepides viridis* exhibited wide seasonal fluctuations, with abundances ranging from 0 - 65/core at GN and from 2 - 105/core at JC (Fig. 7D-E). Although most seasonal values were in the range of previous values, at both stations the June 1986 density was higher than all previous values; the June 1987 density, in contrast, was the lowest density observed during June since 1980.

Multiple regression models accounted for 59% (GN) and 58% (JC) of the variation since 1980, much of which was attributable to the strong seasonal reproductive/recruitment cycles evident in abundances at both stations. After this known variation was removed, no significant trends were evident at either station. In addition, annual adjusted means over 1986 and 1987 were within previous ranges at both stations and there were no significant differences among any of the sampling years.

Paraonis fulgens

Paraonis fulgens is a deposit-feeding polychaete that typically inhabits sandy intertidal beaches (Whitlatch 1977; Strelzov 1979) from Maine to North Carolina (Gosner 1971). This species has typically been among the dominants at only exposed sandy beach stations (GN and WP) and has been found only once at JC. At both GN and WP, *Paraonis fulgens* is generally most abundant in June although peaks have sometimes been recorded in September.

During the last two years, quarterly abundances at WP ranged from 2 - 12/core and from 0 - 20/core at GN (Fig. 7F-G). Abundances at WP in 1986 and 1987 were within the range of past years, although the value obtained in September 1986 was lower than in any previous September. At GN, the range of quarterly values in 1986 was low relative to values in past years; an increase occurred in 1987 and all quarterly values were near the upper end of the range.

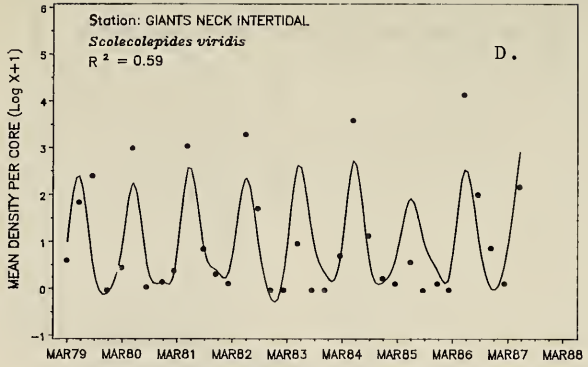
Multiple regression analyses indicated that no significant long-term trends occurred in the abundances of this species at either WP or GN. At WP, despite the consistent decline in annual abundances, there were no significant differences between any sampling years. At GN, the 1987 annual mean was significantly higher than 1986 and also 1980, 1981 and 1984. The 1986 annual mean was significantly lower than 1982.

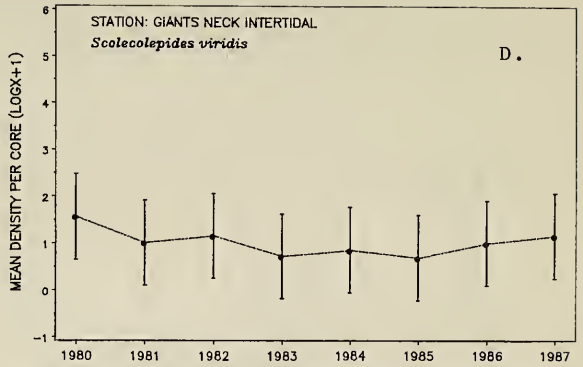
Hediste diversicolor

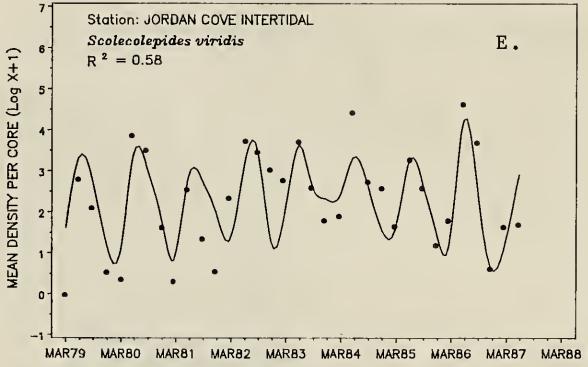
Hediste diversicolor can be found in near-shore waters from the North Atlantic and North Sea to the Mediterranean (Gosner 1971). This omnivorous polychaete is frequently abundant in nutrient rich areas and has been considered an "opportunist" and an "indicator of pollution" (Hull 1987). *Hediste diversicolor* was a consistent dominant at JC, ranking 3rd and 2nd in abundance in 1986 and 1987, respectively. From 1980 through 1985, this species ranked 3rd according to the BIV.

Quarterly density during 1986-87 ranged from 5 - 62/core and most values were within the range of previous years (Fig. 7H). In both years, densities of this species exhibited large seasonal fluctuations with the highest values occurring in September. A similar pattern was observed in 1984 and 1985. The June 1987 mean was the lowest June density observed for this species since 1983.

The multiple regression analysis identified a significant trend in the abundance of *Hediste diversicolor* due to increased abundance from 1982 through 1985. This trend continued through 1986. The increased annual means were primarily due to the high seasonal peaks which became evident in 1984. Annual abundances in 1986 and 1987 were significantly higher than 1982 and 1983; 1986 was also significantly higher than 1980.


Station: GIANTS NECK INTERTIDAL
Scolecolepides viridis
R ² = 0.59
D.
MEAN DENSITY PER CORE (Log X+1)
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88


STATION: GIANTS NECK INTERTIDAL
Scolecolepides viridis
D.
MEAN DENSITY PER CORE (LOGX+1)
1980 1981 1982 1983 1984 1985 1986 1987


Station: JORDAN COVE INTERTIDAL
Scolecolepides viridis
R ² = 0.58
E.
MEAN DENSITY PER CORE (Log X+1)
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88

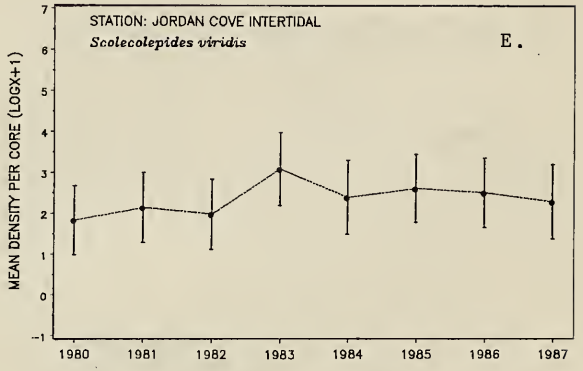
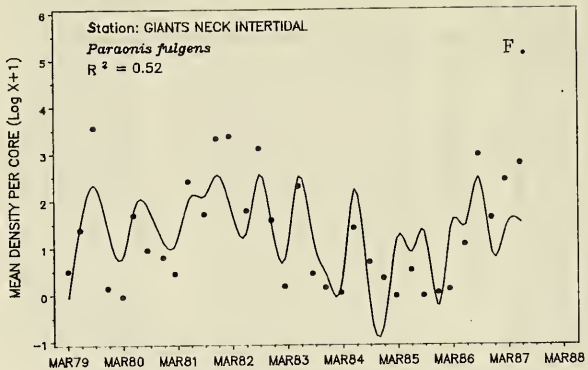
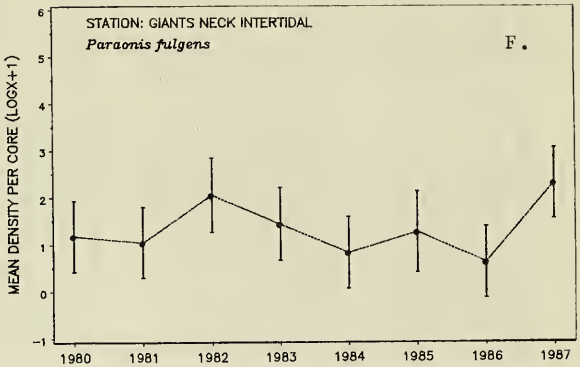
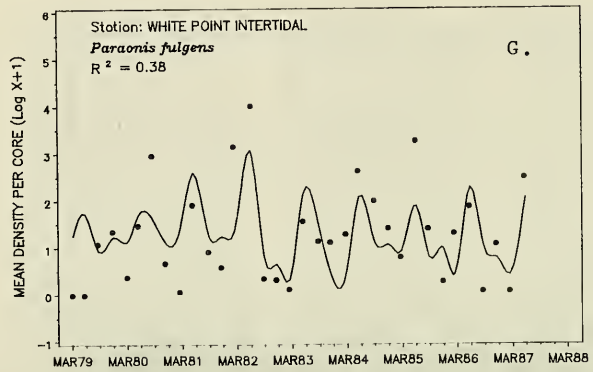

STATION: JORDAN COVE INTERTIDAL
Scolecolepides viridis
E.
MEAN DENSITY PER CORE (LOGX+1)
1980 1981 1982 1983 1984 1985 1986 1987

Fig. 7. Continued.


Station: GIANTS NECK INTERTIDAL
Paraonis fulgens
R ² = 0.52
F.
MEAN DENSITY PER CORE (Log X+1)
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88




Stotion: WHITE POINT INTERTIDAL
Paraonis fulgens
R ² = 0.38
G.
MEAN DENSITY PER CORE (Log X+1)
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88

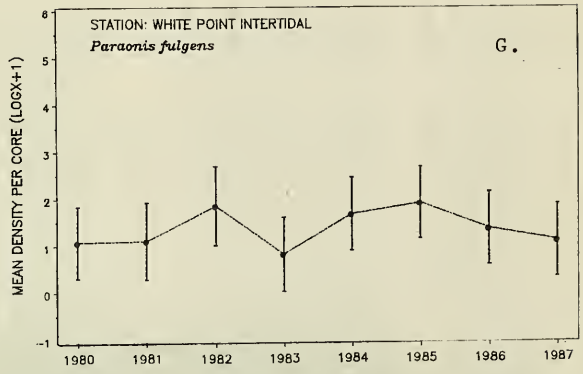
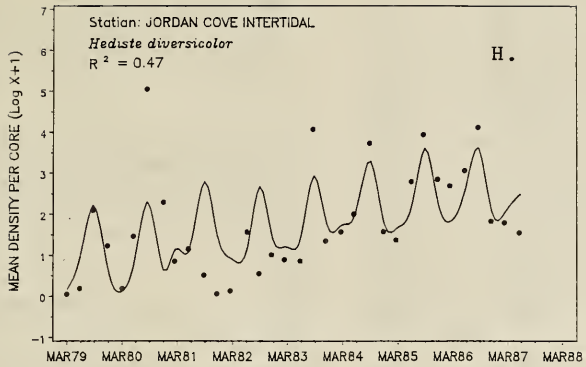


Fig. 7. Continued.


Station: JORDAN COVE INTERTIDAL
Hediste diversicolor
R 2 = 0.47
H.
MEAN DENSITY PER CORE (Log X+1)
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88

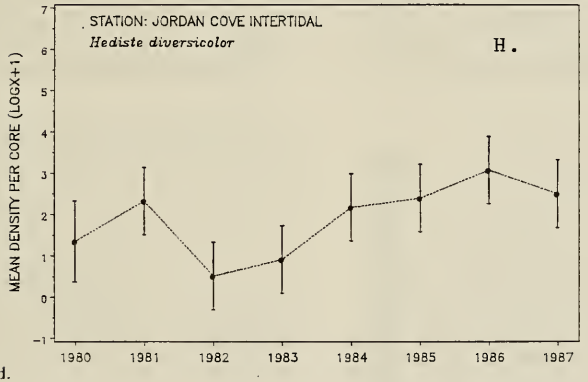
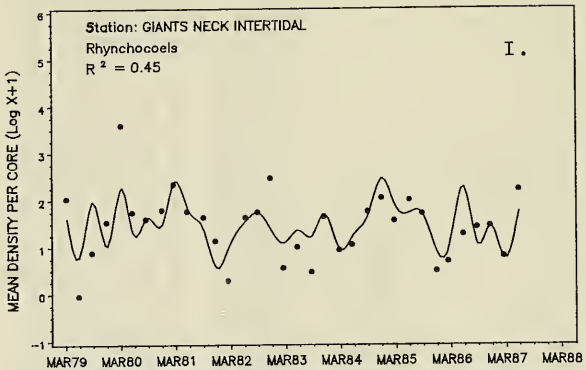

STATION: JORDAN COVE INTERTIDAL
Hediste diversicolor
H.
MEAN DENSITY PER CORE (LOGX+1)
1980 1981 1982 1983 1984 1985 1986 1987

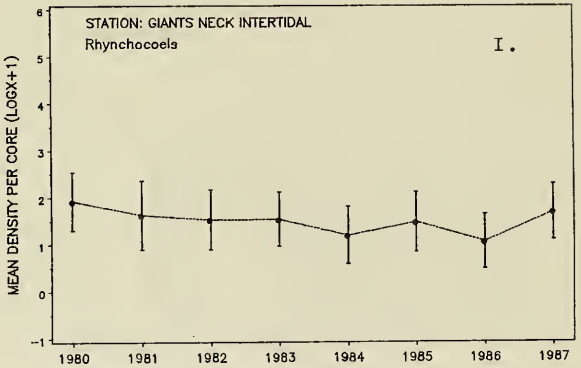
Fig. 7. Continued.

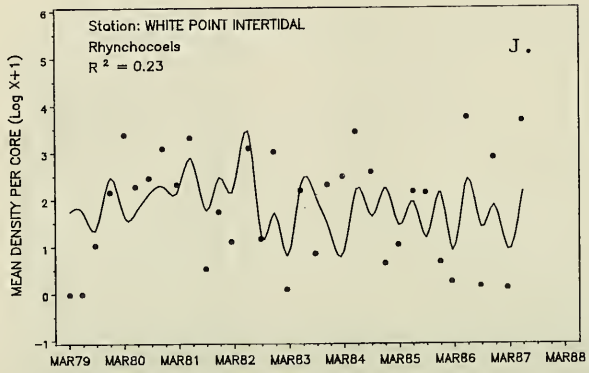
Rhynchocoela

The majority of rhynchocoel species either burrow in the sand or live among seaweeds on rocky shores. Although common in all seas, this group is most common in colder waters. Species which live in mud and sand are excellent burrowers and coupled with their ability to stretch, they are able to escape the beating surf (MacGinitie and MacGinitie 1968). These carnivores have been among the numerical dominants at both GN and WP throughout the monitoring program. They were the most abundant taxa collected at WP during 1986 and 1987. At GN, this taxon was less abundant in 1986-87 (ranking 4th) compared to the 1980-85 period; when it ranked 1st.

During 1986-87, quarterly abundance ranged from 1 - 43/core at WP and from 2 - 10/core at GN (Fig. 7I-J). Seasonal patterns in abundance were evident only at WP, where densities were highest in June in each of the last two years, a pattern consistent with previous years. Abundances at WP during 1986-87 fluctuated widely


Station: GIANTS NECK INTERTIDAL
Rhynchocoels
R ² = 0.45
I.
MEAN DENSITY PER CORE (Log X+1)
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88




Station: WHITE POINT INTERTIDAL
Rhynchocoels
R ² = 0.23
J.
MEAN DENSITY PER CORE (Log X+1)
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88

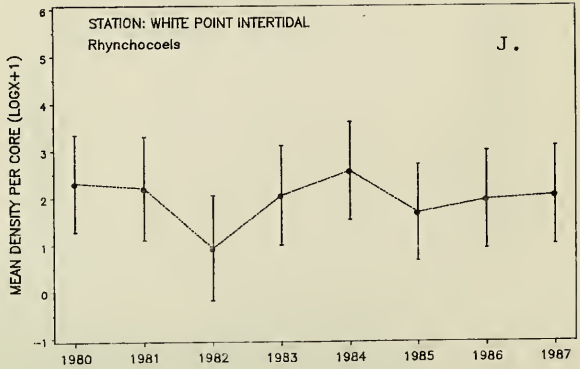


Fig. 7. Continued.

with values near the extremes (high or low) in each sampling quarter. Abundances at GN during this period were well within the range established in previous years, and exhibited much less temporal variation.

After regression analysis removed variation attributable to abiotic factors (23% at WP and 45% at GN), no significant trends in rhynchocoel abundance were evident. In addition, no significant differences were evident among years at either sampling station.

Haploscoloplos fragilis

This burrowing deposit-feeder is capable of ingesting large sand grains and deriving nutrients from the bacterial flora developed upon them. In addition, morphological adaptations allow this species to rapidly burrow through loose unconsolidated sands so that this species can inhabit areas of high sediment movement (Myers 1977).

Haploscoloplos fragilis is a typical dominant of the clean sandy beach communities found at GN and WP where it ranked either 2nd or 3rd in terms of abundance during the last two years. Quarterly densities from September 1985 to June 1987 ranged from 0 - 26/core at GN and 0 - 8/core at WP (Fig. 7K-L). At both stations, this species was most abundant in September and least abundant in March or June. Peak abundances at GN during 1986 and 1987 were generally higher than previous years (except 1985), while at WP they were below those obtained in previous years.

After removing natural variation (72% at GN and 86% at WP), there were no significant long-term trends in density at either station, nor were there any significant differences among sampling years at GN. At WP, the 1986 and 1987 means were significantly different from only 1984.

Species Diversity

Annual mean species diversity (H′) during the past two years ranged from 1.1 - 2.0, evenness (J) from 0.4 - 0.6, and species numbers from 6-17 (Table 3). Lowest diversity of all stations occurred at GN in 1986 (H′ = 1.1) reflecting the generally lower numbers of species and low evenness (due to high densities of *Paraonis fulgens*). All indices at GN for 1987 were within the range of previous years. At JC, H′, S and N were generally higher than other stations in both 1986 and 1987 with 1987 totals reflecting high abundances of *Scolecolepides viridis*, *Hediste diversicolor* and *Fabrica sabella*.

Overall there were no major shifts in parameters used to describe diversity of intertidal communities in 1986 or 1987 relative to the pre-operational period. Although the values of H′, S, and N were lower at WP in both 1986 and 1987, they were still within the historical range.

Cluster Analysis

Cluster analysis produced a dendrogram which showed the very low similarity (-26.0 %) of the JC community to that of WP and GN (Fig. 8). This spatial pattern is consistent with previous years and is due to differences in both patterns of species abundance and composition (NUSCO 1987). During pre-operational and operational years, similarity among the WP (potentially impacted) and GN (reference) communities (Group I) was higher with all years grouping at 45%. This group further divided into three subgroups: Group A contained most GN years; Group B most WP years; and Group C, the 1986 GN and WP years. Within the WP cluster (Group A), the 1987 collection linked with 1982-84, and separated from other years within the group due to similarly low numbers of *Scolecolepides viridis*, *Polydora ligni* and *Capitella* spp.. Within the GN cluster, 1987 chained onto collections made in 1984 and 1985; these shared similarly high numbers of oligochaetes and low numbers of rhynchocoels. Group C contained 1986 GN and WP collections

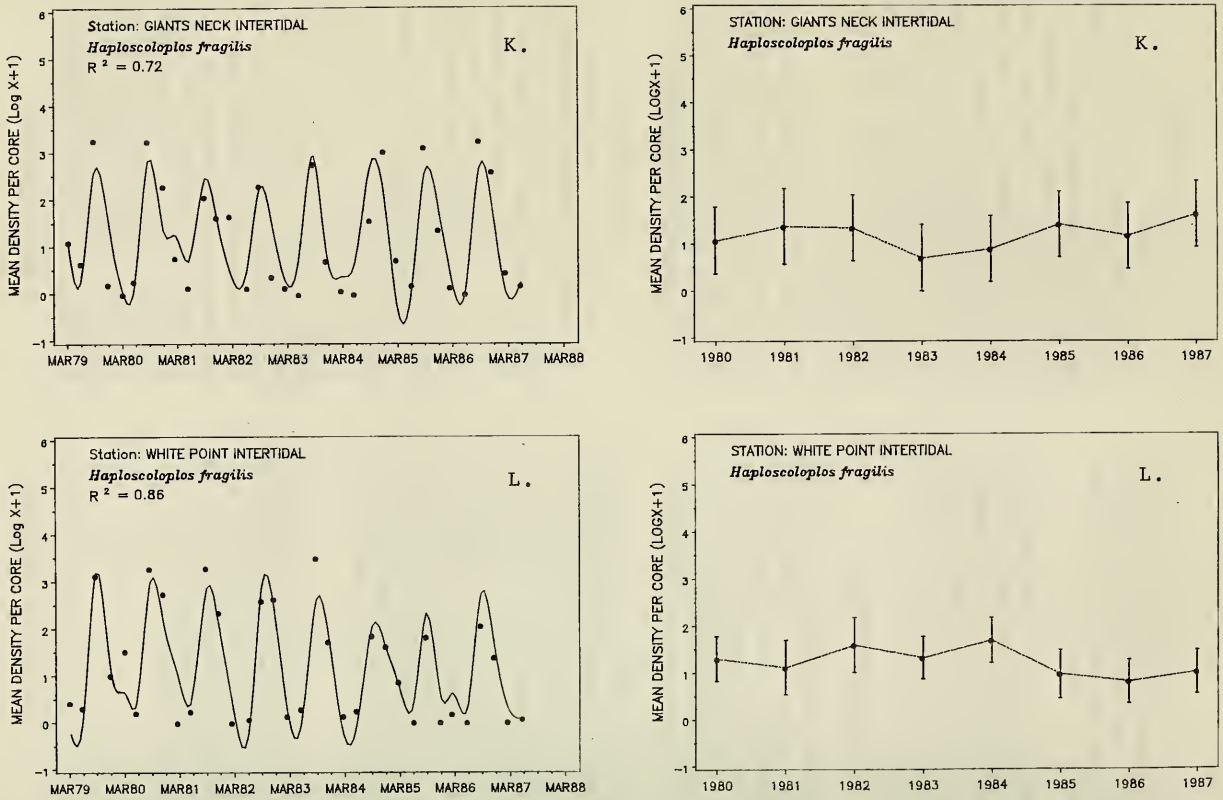

Station: GIANTS NECK INTERTIDAL
Haploscoloplos fragilis
R 2 = 0.72
K.
MEAN DENSITY PER CORE (Log X+1)
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88
STATION: GIANTS NECK INTERTIDAL
Haploscoloplos fragilis
K.
MEAN DENSITY PER CORE (LOGX+1)
1980 1981 1982 1983 1984 1985 1986 1987
Station: WHITE POINT INTERTIDAL
Haploscoloplos fragilis
R 2 = 0.86
L.
MEAN DENSITY PER CORE (Log X+1)
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88
STATION: WHITE POINT INTERTIDAL
Haploscoloplos fragilis
L.
MEAN DENSITY PER CORE (LOGX+1)
1980 1981 1982 1983 1984 1985 1986 1987

Fig. 7. Continued.

TABLE 3. Annual mean species diversity (H'), evenness (J), species number (S) and total individuals (N) (± 1 standard error) for Millstone intertidal stations September 1979 - June 1987.

STATION	1980	1981	1982	1983	1984	1985	1986	1987
GIANTS NECK								
H'	1.9±0.3	1.7±0.2	1.5±0.4	1.3±0.2	2.2±0.5	1.7±0.4	1.1±0.7	1.9±0.3
J	0.7±0.1	0.6±0.1	0.4±0.1	0.5±0.1	0.6±0.1	0.5±0.1	0.4±0.2	0.5±0.1
S	9±3	10±1	13±1	6±1	13±3	9±2	7±2	14±2
N	322±202	202±73	368±61	162±87	220±112	149±54	261±168	351±104
JORDAN COVE								
H'	1.5±0.5	1.7±0.5	1.6±0.5	1.7±0.5	1.5±0.4	2.3±0.1	1.8±0.2	2.0±0.3
J	0.4±0.1	0.4±0.1	0.5±0.2	0.4±0.1	0.5±0.1	0.5±0.1	0.4±0.04	0.5±0.05
S	12±2	15±5	9±2	17±4	12±4	21±3	17±3	14±3
N	267±127	421±160	309±230	558±162	581±249	580±237	917±385	434±279
WHITE POINT								
H'	2.2±0.1	2.1±0.2	1.2±0.2	1.5±0.1	1.4±0.2	1.7±0.4	1.3±0.2	1.3±0.4
J	0.6±0.1	0.7±0.1	0.4±0.1	0.6±0.1	0.4±0.1	0.5±0.1	0.6±0.1	0.5±0.1
S	12±2	11±3	10±2	7±2	10±1	11±2	6±1	7±2
N	193±53	275±101	337±148	97±39	181±63	182±58	62±22	100±37

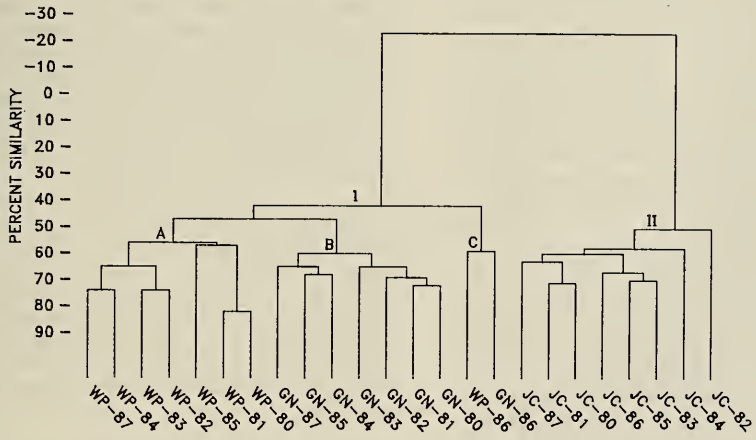


Fig. 8. Dendrogram resulting from the classification of annual intertidal collections at Millstone intertidal stations September 1979 - June 1987.

which shared high densities of *Scolecolepides viridis* and low densities of *Paraonis fulgens*, oligochaetes and *Capitella* spp. In addition, low abundances of *Paraonis fulgens* at GN in 1986 were more comparable to those collected typically at WP in past years (NUSCO 1987).

The JC group (Group II) was subdivided into two smaller groups with 1982 and 1984 collections chaining onto these groups at lower similarity. Collections in the first group, which included 1987, shared relatively low numbers of *Capitella* and *Scolecolepides viridis* and higher numbers of oligochaetes than the second group (1986, 1985 and 1983 collections). The separation of 1984 and 1982 from other sampling years was due to low oligochaete abundances.

Discussion

Intertidal communities sampled during start-up and through the first year of 3-unit operation exhibited spatial patterns in community abundance and composition and seasonal fluctuations in abundance that were consistent with those observed during the baseline period (NUSCO 1987). Higher infaunal abundances and number of species continued to occur at JC, the most sheltered of our sampling stations. Communities at WP, the most exposed station, generally included lower numbers of individuals and species. A similar pattern of increasing density and number of species along gradients of decreasing exposure to wind and wave-induced scour have been reported in many studies (Holland and Dean 1977; Withers and Thorpe 1978; Maurer and Aprill 1979; Tourtellotte and Dauer 1983). At the population level, the JC community continued to be dominated by oligochaetes and other surface deposit-feeding forms whose abundance can be enhanced by the presence of algal and eelgrass detritus (Soulsby et al. 1982; Hull 1987). In contrast, mobile carnivores and large, burrowing deposit-feeding feeding organisms (*Haploscoloplos fragilis*, *Paraonis fulgens*, rhynchocoels, and *Streptosyllis arenae*) which are more typical of exposed habitats (Dexter 1969; Maurer and Aprill 1979; Tourtellotte and Dauer 1983), were consistent dominants at WP and GN. Spatial distributional patterns and seasonal fluctuations evident in Millstone intertidal communities are typical of temperate intertidal beaches, where physical factors such as wind and wave-induced beach scour or the resulting habitat characteristics (e.g., sediment size, silt/clay content, sediment stability and porosity) strongly influence the structure of macrofaunal communities (Green 1969; Holland and Polgar 1976; Croker 1977).

Although spatial patterns were consistent between pre-operational and operational periods, there were temporal changes in community abundance and species composition evident at all sampling stations. Many of these differences appeared to be continuations of trends which were first evident before 3-unit commenced. For instance, increased macrofaunal abundance was observed at JC since 1985, before 3-unit operation started as the result of higher densities of principally oligochaetes. At WP, lower annual community abundance in 1986 continued a trend first evident before 3-unit operation and reflected unusually low numbers of both oligochaetes and polychaetes. At both GN and WP, lower abundances during the 1986-87 were observed in oligochaetes, *Paraonis fulgens*, rhynchocoels and *Haploscoloplos fragilis*. These reductions were evident in December 1985 and March 1986, before 3-unit operation and were evident at our reference station, suggesting that the declines were a response to large-scale regional events. At JC, reductions in total abundance and species number in December 1985 and March 1986 were also evident, although they were not as extensive as those at GN and WP. There were, however, unusually low densities of *Scolecolepides viridis* and *Hediste diversicolor* in June 1987. Low densities of *Scolecolepides viridis* were also evident at GN in June 1987, further indicating a possible area-wide decrease, independent of power plant operations.

During the operational period, several events occurred which might have induced the temporal changes in intertidal community structure and

abundance. First, at JC, and particularly at WP, there was an increase in sediment grain size starting in June 1985, and continuing through March 1987. Since no corresponding increase occurred at GN, this change was not attributable to a regional climatic event. Neither was it likely to be power plant-related because the change was evident before operation of Unit 3. Increased grain size at WP was accompanied by a reduction in oligochaetes, although few other taxa seemed affected. Lower oligochaete abundances in 1986 may have been a response to reduced food availability given the increased grain size. At JC, although sediment size increased, levels of silt/clay content were within the historical range and no changes in macrofaunal communities could be attributed to the observed changes in sediment characteristics.

The second event that occurred during this study was the passage of Hurricane Gloria (September 1985). This storm passed within 72 km of the Millstone sampling area, producing winds nearing 161 km/h. Following the storm, lower abundances and species number were observed (December 1985 and March 1986) at all monitoring stations. This contrasts however, with other studies reporting surprisingly minor effects on interidal communities after hurricanes (Croker 1968; Saloman and Naughton 1977). Studies in the Millstone area (Dobbs and Vozarik 1983) identified only minor rearrangements in community dominance patterns in the shallow subtidal area adjacent to our JC intertidal station associated with the passage of Hurricane David.

Conclusions

Sampling of intertidal communities during 1986-87 revealed no immediate changes to these communities which could be directly attributed to Unit 3 start-up or to 3-unit operations at MNPS. Spatial distribution and abundance patterns of dominant species at the intertidal stations were consistent with those observed during baseline studies. Major temporal shifts observed over 1986-87 appeared to be mediated by natural shifts in grain size and passage of Hurricane Gloria. Given the limited 3-unit operational history, additional data will be needed before subtle impacts (like those due to plant-related temperature increases) can be assessed.

Subtidal Results

Sedimentary Environment

Sediments at subtidal stations from September 1985 - June 1987 were comprised of very fine to coarse sands which ranged in size from 0.07 - 0.55 mm and contained from < 1 - 44% silt/clay (Fig. 9). During this period, sediments were generally coarsest at EF, where medium sands (0.31 - 0.50 mm in size) of low silt/clay (0.7%- 5.17%) content predominated. At this station, there was a trend for increasing grain size and decreased silt/clay content beginning in September 1985 and continuing through June 1987.

Grain size at GN ranged from 0.21 - 0.55 mm and although fine-to-medium sands predominated at this station, coarse sediments were obtained in September 1985. The seasonal trend of coarse sediments during September also occurred in 1983 and 1984, but not during 1986 or 1987. Silt/clay at this station ranged from 10 to 20% with no consistent seasonal periodicity. During 1986-87, grain size and silt/clay content at this station were consistent with past results (NUSCO 1987).

Sediments at IN ranged from 0.07 - 0.21 mm (very fine - fine sand) since September 1985, and were within the range of those collected in previous years (NUSCO 1987). Silt/clay content at this station remained high, relative to other stations, and ranged from 5.8 - 44.5%. Higher and more variable values were obtained during 1986 than in 1987.

Temporal fluctuations in sedimentary characteristics also occurred at JC during the 1986 - 1987 sampling period. Quarterly mean grain size ranged from 0.10 mm - 0.52 mm (very fine to coarse sands) and silt/clay from 3.9 - 38%. From September 1986 through June 1987, values for grain size at this station were lower than all previous observations. Silt/clay values during 1986 were consistent with those observed in past years (NUSCO 1987). During 1987 sampling, levels of silt/clay within JC sediments generally exceeded those obtained in previous years.

During the operational period, changes in sedimentary characteristics at all stations, except GN, were apparently related to start-up of Millstone Unit 3. At EF, the increased grain size and decreased silt/clay content was attributable to scouring produced by the 3-unit discharge. At JC, unusually high silt/clay content was detected in September 1986, although divers reported reduced visibility and unusually turbid conditions at this sampling station as early as June. Reduced silt/clay at IN also corresponded to power plant start-up. There was no comparable shift at the GN reference station, which might indicate that a natural event was responsible for the changes which occurred at other stations.

General Community Composition

The general composition of subtidal communities sampled during 1986 - 1987 is presented in Table 4. Polychaetes were most abundant, and during 1986 and 1987 accounted for 66 - 56% of the total individuals collected at GN and JC, respectively. Oligochaetes were the second most abundant group at these stations in 1986. In 1987, total arthropod abundance doubled at GN and increased by an order of magnitude at JC. Oligochaetes dominated at EF (46% and 50%) followed by polychaetes (36% and 28%). The large increase in arthropods observed at GN and JC during 1987 was not evident at EF where total numbers collected were near the lower end of the range in both 1986 and 1987. Arthropods were the major component of IN communities during both 1986 and 1987, accounting for 54% and 67% of the total individuals, respectively. Polychaetes were the second most abundant group, followed by molluscs.

Polychaetes were the most diverse group and accounted for the majority of infaunal species

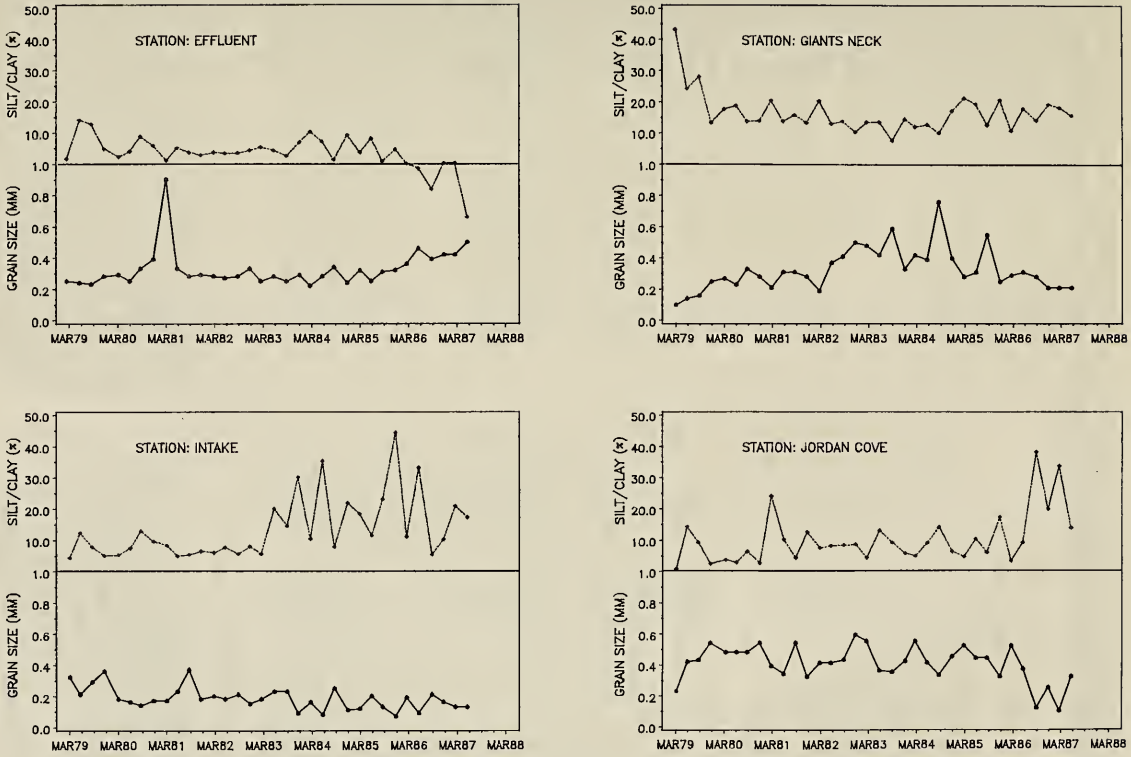


Fig. 9. Quarterly mean grain size (mm) and silt/clay content (%) of sediments sampled at Millstone subtidal stations from March 1979 - June 1987.

TABLE 4. Number of species (S), number of individuals (N) and percentage of the total (%) for each major taxon collected at Millstone subtidal stations September 1985 - June 1987, with ranges from 1980-85.

STATION	Range 1980-1985			1986			1987		
	S	N	%	S	N	%	S	N	%
EFFLUENT									
Polychaeta	62-75	2464-7849	39-73	57	2213	36	58	2079	28
Oligochaeta	-	1470-4496	18-47	-	2848	46	-	3815	50
Mollusca	25-34	140-934	2-8	30	429	7	28	638	8
Arthropoda	32-45	318-1412	4-12	26	558	9	36	580	8
Rhynchocoela	-	47-245	1-2	-	92	1	-	195	3
'Others'	0-5	0-35	0-1	5	75	1	6	240	3
GIANTS NECK									
Polychaeta	57-74	4262-9527	58-79	75	6590	66	69	8946	66
Oligochaeta	-	962-2658	13-30	-	1896	19	-	2116	16
Mollusca	12-27	49-443	1-5	30	332	3	29	215	2
Arthropoda	31-42	535-761	5-12	45	1029	10	42	2154	16
Rhynchocoela	-	28-107	< 1-1	-	56	< 1	-	74	< 1
'Others'	0-4	0-23	0-1	4	25	< 1	6	11	< 1
INTAKE									
Polychaeta	38-47	737-1358	18-66	54	1869	32	49	2930	26
Oligochaeta	-	86-354	4-17	-	170	3	-	164	1
Mollusca	12-24	61-417	3-14	17	579	10	22	606	5
Arthropoda	19-31	196-2749	10-67	26	3124	54	28	7624	67
Rhynchocoela	-	7-33	< 1-1	-	24	< 1	-	52	< 1
'Others'	0-2	0-3	0- < 1	1	2	< 1	5	4	< 1
JORDAN COVE									
Polychaeta	52-70	2276-13357	37-57	62	5136	56	64	10462	66
Oligochaeta	-	195-7811	5-59	-	3106	34	-	2040	13
Mollusca	14-32	109-760	1-6	32	605	6	27	699	4
Arthropoda	20-31	242-2412	2-4	35	266	3	29	2650	17
Rhynchocoela	-	56-125	1	-	88	1	-	85	< 1
'Others'	0-6	0-8	0- < 1	4	10	< 1	6	13	< 1

during 1986 and 1987. The number of polychaete species ranged from 49 (IN) to 75 (GN). Arthropods were the second most diverse group at GN, JC and IN. The numbers of mollusc species were similar to the numbers of arthropods at all stations.

When results obtained over the last two years were compared to those of the 1980-85 period, differences in overall community composition were evident. There was a general trend in 1986 and 1987 for higher species number and abundances at GN, IN and JC, but not at EF. Although most observations for 1986-87 were within the range of previous years, values tended to be nearer the upper bounds than lower ones. For example, numbers of molluscs and arthropod species, as well as the abundance of arthropods col-

lected at GN were at or above the previous years' ranges. Similarly, the numbers of polychaete species and abundance of polychaetes, molluscs and arthropods at IN were above the previous ranges. Most values for JC were within the range of previous years and the most notable change was in the high numbers of arthropods observed in 1987. At EF, the overall trend was for lower numbers of species and abundances.

Community Abundance

The log-transformed quarterly mean abundances of subtidal communities since 1980 are presented in Figure 10. Densities during 1986-87 ranged from 67 - 208/core at EF, 181 - 455/core (exponential of values in Figure 10) at GN, 27 - 503/core at IN and 138 - 600/core at JC . Except for June 1987 at IN and GN, values obtained in the last two years were within the range established in previous years. Although within the range, abundances at EF, IN and JC in March 1986 were among the lowest ever recorded for these stations. Levels near the upper extremes also occurred in the last two years (e.g., December 1985, March and June 1986 at IN, September 1986 at JC, and June 1987 at GN). No comparable peaks were evident at EF.

Multiple regression analyses, which accounted for 43, 54, 57 and 44% of the total variation at EF, GN, IN and JC, respectively, revealed no significant trends in community abundance at any subtidal station. However, pair-wise comparisons revealed significant interannual differences at all stations.

At EF, the 1986 mean was significantly lower than 1984, when peak abundances occurred. Abundances at JC in 1986 were significantly lower than 1980, 1984 and 1987. The 1987 mean was also significantly higher than 1982. Of all communities, IN exhibited the largest change in abundance during the last two years; 1986 and 1987 were significantly higher than annual means from 1981-1984. Annual mean densities at GN were near (1986) or exceeded (1987) the range observed since 1980, but both were significant from only 1983. The 1987 mean was also significantly higher than 1980.

Number of Species

In 1986-87, mean quarterly number of species comprising subtidal communities from 1986-87 ranged between 19-37/core at EF, 21-37/core at GN, 12-29/core at IN and 18-37/core at JC (Fig. 11). Lowest number of species during this period occurred in March 1987, at GN and EF and in March 1986, at IN and JC. Highest values at all stations were obtained in June 1987. All quarterly values, except in June 1987 at IN, were within the range observed during the 1980-85 period.

After removing variation attributable to explanatory variables, significant trends were evident in species number at IN, EF, and GN. An increasing trend in annual adjusted means was evident at IN; the 1986 mean was significantly higher than only 1984, but 1987 was significantly higher than all previous years except 1985. At EF, a significant increasing trend was during the pre-operational period; this trend reversed in 1986, which was significantly lower than 1984 and 1985. The 1987 mean was also lower than 1985 but not 1984. At GN, a significant increasing trend began in 1984. Values obtained in in 1986 were significantly higher than those obtained from 1981-1983, while 1987 was significant from only 1981. Jordan Cove was the only community where a significant trend in species number did not occur and pair-wise comparisons of annual means revealed significant differences only between 1987 and 1982.

Community Dominance

A list of all taxa ranking among the top ten in abundance for 1986 and 1987 and over the 1980-85 period is presented in Table 5. In the last two years, 6 of 7 top ranked organisms (according to the BIV) were the same at JC and GN and four of these were also among the top dominants at EF. *Mediomastus ambiseta* was the most consistently dominant organism at GN, JC and IN in

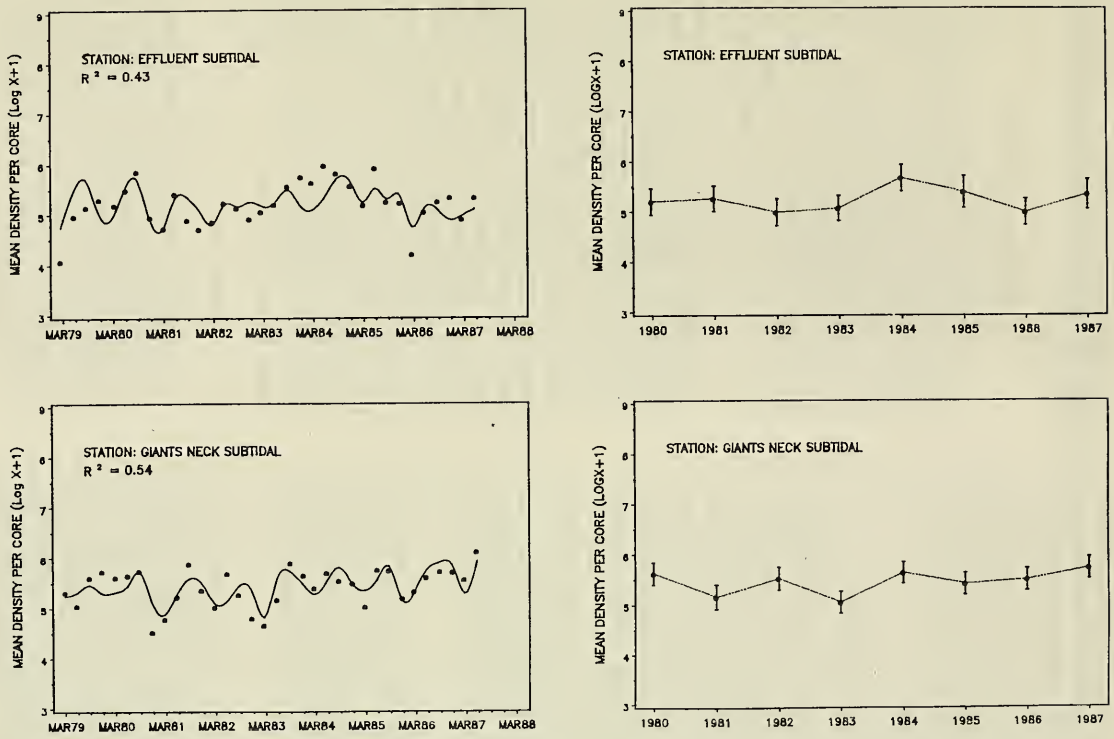

STATION: EFFLUENT SUBTIDAL
R ² = 0.43
MEAN DENSITY PER CORE (Log X+1)
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88
STATION: EFFLUENT SUBTIDAL
MEAN DENSITY PER CORE (LOGX+1)
1980 1981 1982 1983 1984 1985 1986 1987
STATION: GIANTS NECK SUBTIDAL
R ² = 0.54
MEAN DENSITY PER CORE (Log X+1)
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88
STATION: GIANTS NECK SUBTIDAL
MEAN DENSITY PER CORE (LOGX+1)
1980 1981 1982 1983 1984 1985 1986 1987

Fig. 10. Quarterly means of log-transformed abundance ((LN(X + 1)), multiple regression predictions, and adjusted annual abundances of Millstone subtidal infaunal communities from March 1979 - June 1987. (Annual means were adjusted using analysis of covariance which included abiotic and climatic conditions as covariates. Error bars represent ± 2 SE.)

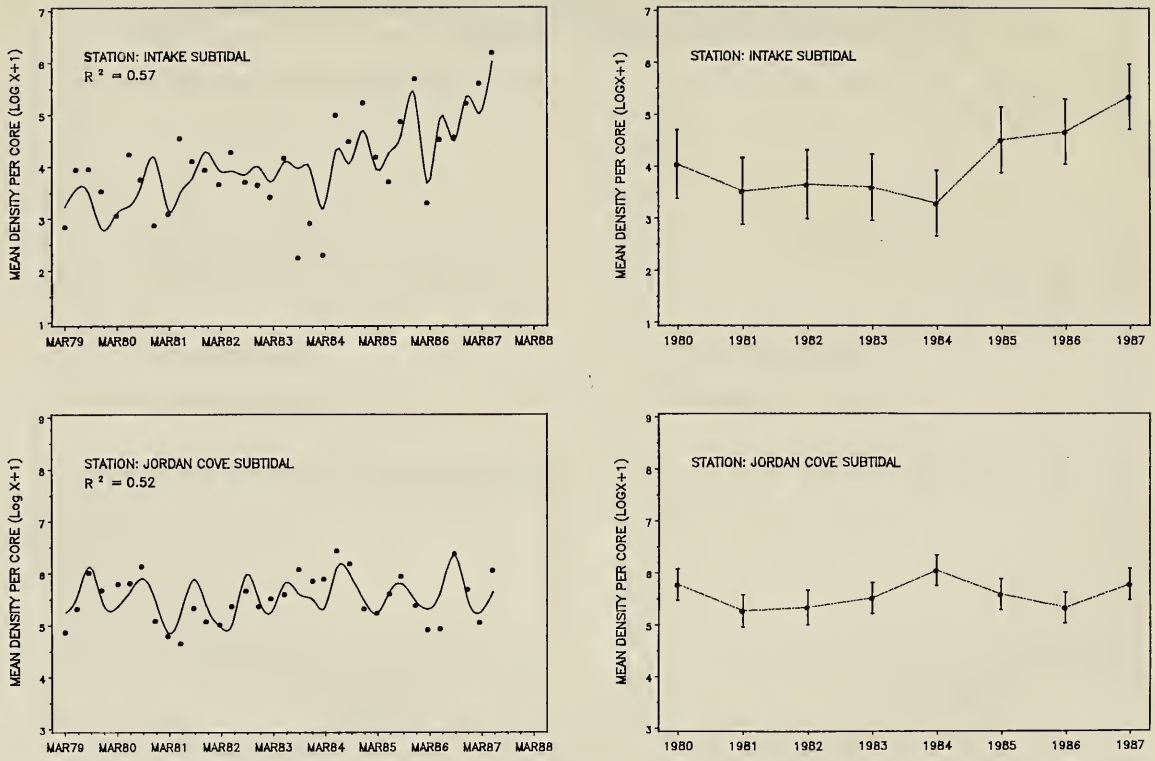

STATION: INTAKE SUBTIDAL
R ² = 0.57
MEAN DENSITY PER CORE (LOG X+1)
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88
STATION: INTAKE SUBTIDAL
MEAN DENSITY PER CORE (LOGX+1)
1980 1981 1982 1983 1984 1985 1986 1987
STATION: JORDAN COVE SUBTIDAL
R ² = 0.52
MEAN DENSITY PER CORE (Log X+1)
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88
STATION: JORDAN COVE SUBTIDAL
MEAN DENSITY PER CORE (LOGX+1)
1980 1981 1982 1983 1984 1985 1986 1987

Fig. 10. Continued.

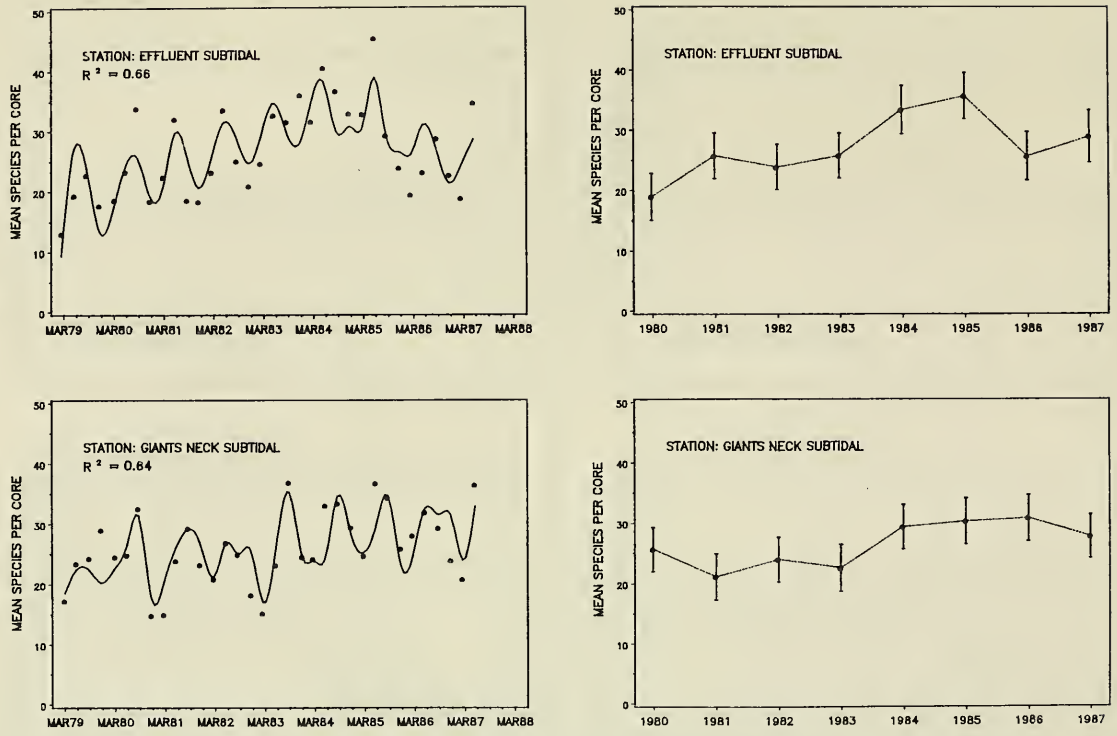

STATION: EFFLUENT SUBTIDAL
R ² = 0.66
MEAN SPECIES PER CORE
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88
STATION: EFFLUENT SUBTIDAL
MEAN SPECIES PER CORE
1980 1981 1982 1983 1984 1985 1986 1987
STATION: GIANTS NECK SUBTIDAL
R ² = 0.64
MEAN SPECIES PER CORE
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88
STATION: GIANTS NECK SUBTIDAL
MEAN SPECIES PER CORE
1980 1981 1982 1983 1984 1985 1986 1987

Fig. 11. Quarterly means of number of species, multiple regression predictions, and adjusted annual number of species of Millstone subtidal infaunal communities from March 1979 - June 1987. (Annual means were adjusted using analysis of covariance which included abiotic and climatic conditions as covariates. Error bars represent ±2 SE.)

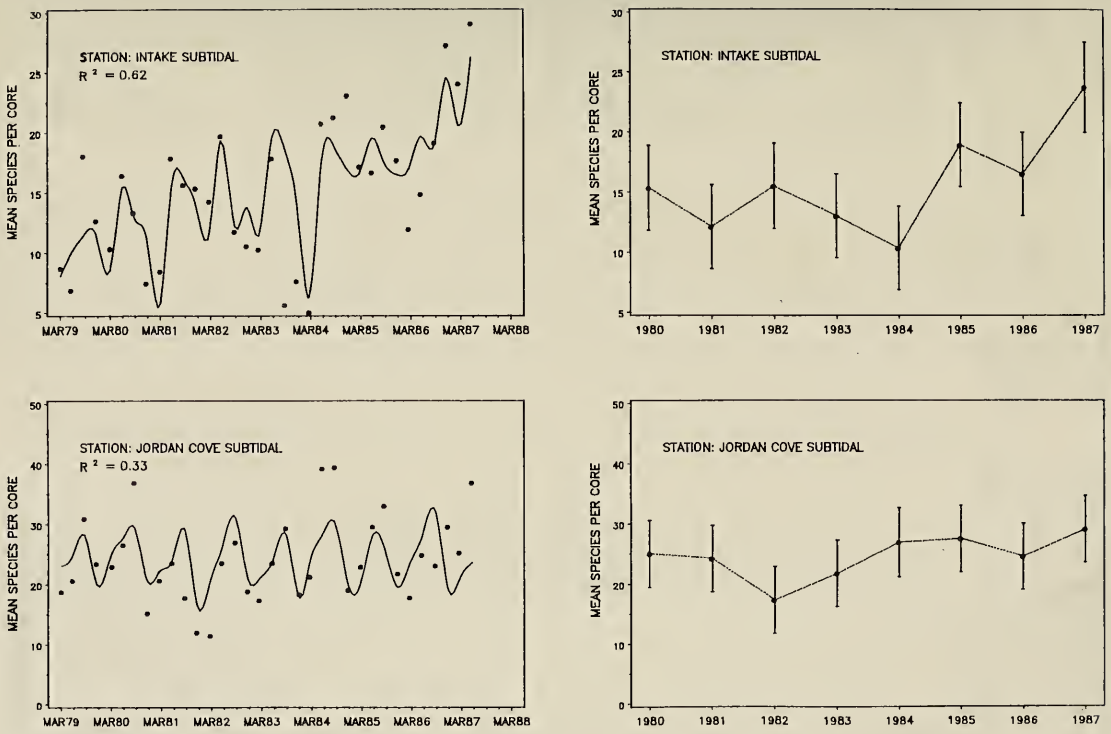

STATION: INTAKE SUBTIDAL
R ² = 0.62
MEAN SPECIES PER CORE
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88
STATION: INTAKE SUBTIDAL
MEAN SPECIES PER CORE
1980 1981 1982 1983 1984 1985 1986 1987
STATION: JORDAN COVE SUBTIDAL
R ² = 0.33
MEAN SPECIES PER CORE
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88
STATION: JORDAN COVE SUBTIDAL
MEAN SPECIES PER CORE
1980 1981 1982 1983 1984 1985 1986 1987

Fig. 11. Continued.

TABLE 5. Mean number of individuals per core and Biological Index Value (BIV) of the ten most numerically abundant taxa collected at the Millstone subtidal stations September 1985 - June 1987, with annual range and mean (no./core) for 1980-1985.

	1980-85		1986	1987	1980-85	1986-87
Station	Range	Mean	Mean	Mean	BIV	BIV
EFFLUENT						
Oligochaeta	37 - 112	72	71	95	99.0	100.0
Mediomastus ambiseta	< 1 - 26	7	14	11	61.5	92.3
Protodorvillea gaspeensis	2 - 15	8	8	9	86.8	80.7
Tharyx dorsobranchialis	< 1 - 11	4	9	2	67.3	57.7
Ampelisca verrilli	< 1 - 5	1	7	3	46.6	57.7
Rhynchocoela	1 - 6	3	2	5	69.2	53.8
Tellina agilis	1 - 12	6	6	3	71.4	50.0
Owenia fusiformis	0 - < 1	< 1	1	6	-	46.1
Mytilus edulis	0 -1	< 1	< 1	6	-	42.3
Archiannelida	< 1 - 3	2	< 1	6	-	42.3
Spiophanes bombyx	0 - < 1	< 1	< 1	4	-	34.6
Ampelisca vadorum	< 1 - 4	1	2	1	-	26.9
Polycirrus eximius	8 - 100	31	2	< 1	82.2	23.1
Aricidea catherinae	2 - 21	8	< 1	< 1	62.3	-
Tharyx acutus	2 - 76	21	0	0	54.6	-
Exogone hebes	2 - 4	3	1	< 1	53.6	-
Capitella spp.	< 1 - 4	2	2	1	52.6	-
Eumida sanguinea	< 1 - 7	3	< 1	< 1	49.5	-
Caulleriella spp.	< 1 - 3	2	2	2	48.1	-
Lumbrineris tenuis	< 1 - 6	2	1	1	46.2	-
Polydora caulleryi	0 - 7	3	1	1	44.0	-
Pagurus acadianus	< 1 - 6	2	1	2	41.3	-
Microphthalmus aberrans	< 1 - 2	1	1	2	40.6	-
Leptocheirus pinguis	< 1 - 5	2	1	2	39.4	-
Prionospio steenstrupi	< 1 - 3	1	< 1	2	36.8	-
Gammarus lawrencianus	< 1 - 4	1	< 1	< 1	25.7	-
GIANTS NECK						
Mediomastus ambiseta	2 - 73	19	35	77	60.2	91.7
Oligochaeta	24 - 66	48	47	53	94.4	87.5
Aricidea catherinae	27 - 88	47	24	59	94.4	83.3
Tharyx dorsobranchialis	20 - 48	31	58	32	90.7	83.3
Protodorvillea gaspeensis	4 - 11	7	8	11	68.5	58.3
Lumbrineris tenuis	2 - 8	5	8	7	53.2	45.8
Leptocheirus pinguis	< 1 - 4	1	1	37	17.6	45.8
Exogone dispar	1 - 12	5	5	8	48.6	41.7
Ampelisca abdita	< 1 - 2	1	1	9	-	41.7
Ampelisca vadorum	< 1 - 1	< 1	4	4	-	25.0
Spio setosa	0 - < 1	< 1	6	< 1	-	25.0
Unciola irrorata	0 - < 1	< 1	0	4	-	20.8
Tharyx acutus	4 - 37	15	0	0	75.9	-
Polycirrus eximius	1 - 13	7	3	1	58.3	-
Phoxocephalus holbolli	2 - 9	5	3	2	51.4	-
Polydora caulleryi	< 1 - 10	4	2	2	42.6	-
Prionospio steenstrupi	1 - 6	3	2	2	35.2	-
Capitella spp.	1 - 4	2	1	3	34.7	-
Gammarus lawrencianus	0 - 6	2	< 1	2	33.8	-
Eumida sanguinea	< 1 - 3	2	1	1	32.4	-
Lumbrineris impatiens	0 - 8	2	0	0	32.4	-
Polydora quadrilobata	< 1 - 6	2	< 1	2	25.5	-

- = not among the ten most numerically abundant taxa

TABLE 5. cont'd

Station	1980-85 Range	1980-85 Mean	1986 Mean	1987 Mean	1980-85 BIV	1986-87 BIV
INTAKE						
Mediomastus ambiseta	< 1 - 10	3	34	31	60.1	92.9
Ampelisca abdita	< 1 - 25	5	54	18	49.0	89.3
Ampelisca verrili	< 1 - 11	4	8	12	70.5	75.0
Ampelisca vadorum	< 1 - 8	2	11	11	45.5	71.4
Leptocheirus pinguis	0 - 17	4	1	125	50.0	62.5
Owenia fusiformis	0 - < 1	< 1	1	22	-	55.4
Oligochaeta	2 - 9	6	4	4	93.1	53.6
Nucula proxima	< 1 - 4	1	6	4	52.1	53.6
Tellina agilis	1 - 5	2	4	4	67.0	42.9
Unciola irrorata	0 - 1	< 1	0	12	-	37.5
Lacuna vincta	< 1 - < 1	< 1	3	2	-	32.1
Tharyx dorsobranchalis	< 1 - < 1	< 1	3	3	-	32.1
Pagurus longicarpus	0 - 1	< 1	0	10	-	30.4
Prionospio steensturpi	< 1 - 3	1	1	< 1	49.0	21.4
Aricidea catherinae	< 1 - 7	4	1	3	79.2	-
Capitella spp.	< 1 - 6	2	1	2	67.4	-
Exogone hebes	< 1 - 4	2	< 1	1	64.9	-
Tharyx acutus	< 1 - 5	2	0	0	62.8	-
Spiophanes bombyx	< 1 - 4	1	< 1	2	57.6	-
Unicola serrata	< 1 - 4	1	1	< 1	57.3	-
Protodorvillea gaspeensis	< 1 - 2	1	< 1	< 1	46.2	-
Gammarus lawrencianus	< 1 - 4	1	< 1	< 1	45.4	-
Clymenella torquata	0 - 5	1	0	1	41.7	-
Polydora quadrilobata	< 1 - 2	1	< 1	1	39.9	-
Pygospio elegans	0 - 2	1	0	0	38.9	-
Polydora ligni	0 - 9	2	< 1	< 1	36.1	-
Phyllodoce mucosa	0 - 1	< 1	< 1	< 1	29.5	-
Sabellaria vulgaris	0 - 3	< 1	< 1	< 1	24.3	-
Crangon septemspinosus	0 - 2	< 1	1	< 1	22.6	-
JORDAN COVE						
Mediomastus ambiseta	1 - 197	51	45	170	77.6	96.7
Oligochaeta	92 - 195	119	78	51	99.1	93.3
Aricidea catherinae	29 - 65	41	27	17	92.1	83.3
Lumbrineris tenuis	4 - 23	13	9	12	80.7	76.7
Tharyx dorsobranchialis	3 - 14	7	8	10	67.5	70.0
Leptocheirus pinguis	< 1 - 5	2	1	60	26.8	53.3
Polycirrus eximius	2 - 25	12	7	4	79.8	46.7
Microphthalmus aberrans	< 1 - 3	1	2	9	-	43.3
Prionospio steenstrupi	< 1 - 3	1	4	5	28.9	43.3
Tellina agilis	1 - 8	4	3	5	50.0	36.7
Polydora caulleryi	< 1 - 25	7	5	1	48.7	36.7
Capitella spp.	1 - 8	4	1	6	52.2	33.3
Pholoe minuta	1 - 3	2	1	6	34.2	30.0
Mitrella lunata	< 1 - 1	< 1	4	3	-	30.0
Spio setosa	< 1 - < 1	< 1	4	< 1	-	26.7
Tharyx acutus	1 - 7	4	< 1	0	55.3	-
Rhynchocoela	1 - 3	2	2	2	43.9	-
Eumida sanguinea	< 1 - 5	2	1	1	40.4	-
Lumbrineris impatiens	0 - 6	2	< 1	1	36.8	-
Parapionosyllis longicirrata	1 - 5	2	1	< 1	35.5	-
Exogone hebes	< 1 - 3	2	2	1	31.1	-
Gammarus lawrencianus	< 1 - 3	1	< 1	< 1	19.3	-

- = not among the ten most numerically abundant taxa

1986-87. At EF, oligochaetes were the most abundant (71 - 95/core) and consistently dominant taxa during 1986-87. Oligochaetes ranked second at GN and JC, while the ampeliscid amphipod, *Ampelisca abdita* ranked second at IN. *Aricidea catherinae* and *Lumbrineris tenuis* were dominant in both years at GN and JC. *Leptocheirus pinguis* appeared among the dominants at all stations except EF in 1987.

The IN community, in addition to the top ranking *Mediomastus ambiseta*, was dominated by three amphipods, *Ampelisca abdita*, *A. verrilli*, and *A. vadorum*. *Leptocheirus pinguis*, however, was the most abundant organism (125/core) in 1987, but was not abundant in 1986. Other species present in abundance (> 10/core) at IN in 1987 were: the tube building polychaete, *Owenia fusiformis* the amphipod, *Uniciola irrorata* and the hermit crab, *Pagurus longicarpus*.

When compared to 1980-85, there were changes in the dominance structure over 1986-87 relative to 1980-85; most of these were first apparent in 1987. A regional change occurred in the abundance of arthropods, particularly *Leptocheirus pinguis*. Abundance of this species, as well as other arthropods (*Uniciola irrorata*, *Ampelisca abdita* and *A. vadorum*), at GN, JC and IN during 1987 were well above the 5-year average. A second area-wide change in dominance occurred in densities of *Mediomastus ambiseta*. This species had a high BIV (> 90%) during 1986-87 at all stations compared to the range for 1980-85 (60.1-77.6%).

In 1986-87, 3 taxa at EF, 2 at GN and IN and 1 at JC were among the top ten for the first time. All newly ranked species were generally abundant in only one of the last two years and had low 1986-87 BIV's. The number of species included among the dominants in 1980-85, but not during 1986-87 were greater, although the majority of these had low BIV's for 1980-85 or were collected in low abundances. Those species with high 5-year BIV's (> 70%) or high mean abundance (> 10/core) and not among the top ten in 1986-87 were: *Tharyx acutus* and *Polycirrus eximius* at GN and EF and *Aricidea catherinae* at IN. *Polycirrus eximius* was aslo found in lower density at JC in the last two years, although this species remained among the top ten. Changes in abundance of dominant taxa will be described in more detail in the following section.

Dominant Taxa

Temporal patterns in abundance of selected subtidal taxa were examined using the same multiple regression analysis procedure used to remove natural sources of variation in abundance and number of species. Taxa selected ranked among the top four numerical dominants (BIV's > 80%) during either the 1980-85 pre-operational period, or the 1986-87 operational period. In some cases, taxa were included to allow comparison at all stations, even though the BIV may not exceed 80% (e.g., *Aricidea catherinae* at EF). Quarterly and annual means plotted in the figures are log-transformed; those described in the text are the exponentials of plotted values.

Oligochaetes

These annelids occupy a variety of habitats in the Millstone area, and feed on the fine deposits incorporated into the sediments. Oligochaete densities can increase both quickly (Giere 1975) and markedly (Price and Hylleberg 1982) as the amount of detritus incorporated in sediments increases. Oligochaetes were a dominant taxon at 3 of the 4 subtidal stations; at EF this group ranked 1st in both 1986 and 1987; 3rd at GN and 2nd at JC in terms of the 2-year BIV. Oligochaetes ranked 7th at IN over 1986-87.

Throughout the operational period, oligochaete abundance ranged from 35 - 56/core at GN, 23 - 123/core at JC, 23 - 127/core at EF and from 1 - 6/core at IN (Fig. 12A-D). Oligochaete abundance at GN, EF and IN was within the range of previous years while at JC, densities from March 1986 - June 1987 were at their lowest level since June 1981.

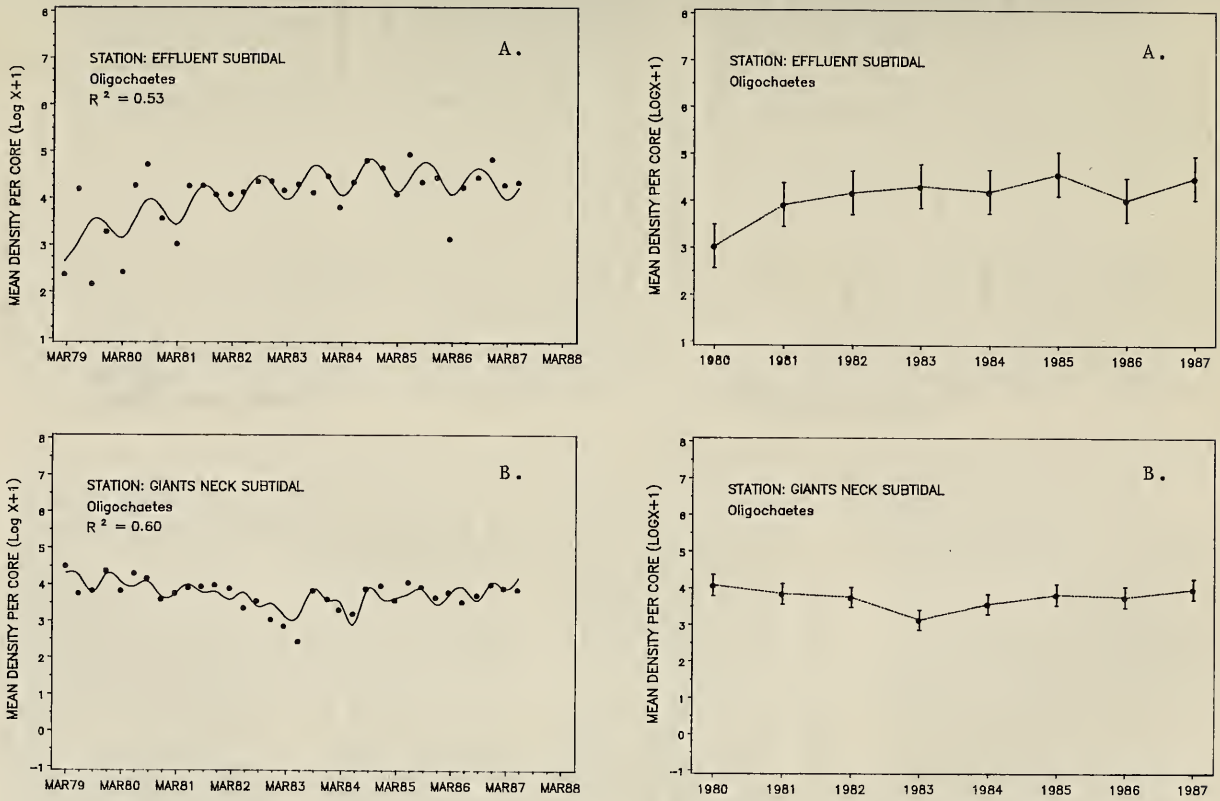
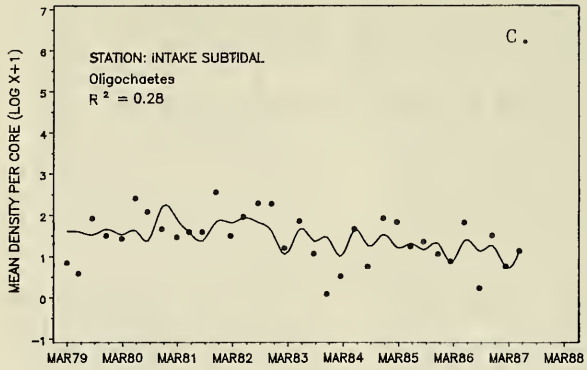
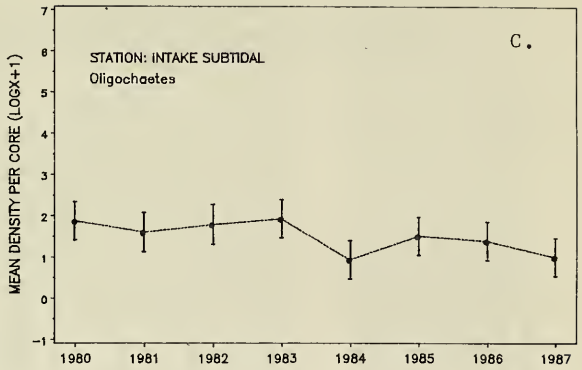
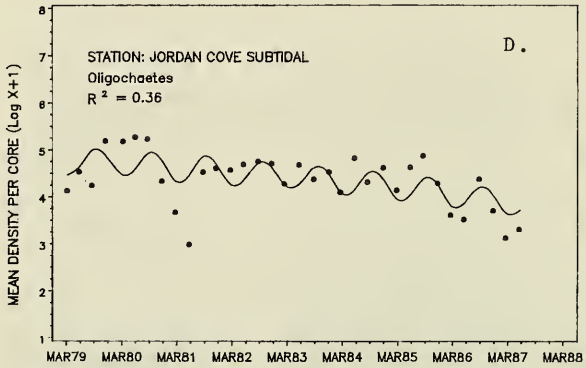

STATION: EFFLUENT SUBTIDAL
Oligochaetes
R ² = 0.53
A.
MEAN DENSITY PER CORE (Log X+1)
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88
STATION: EFFLUENT SUBTIDAL
Oligochaetes
A.
MEAN DENSITY PER CORE (LOGX+1)
1980 1981 1982 1983 1984 1985 1986 1987
STATION: GIANTS NECK SUBTIDAL
Oligochaetes
R ² = 0.60
B.
MEAN DENSITY PER CORE (Log X+1)
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88
STATION: GIANTS NECK SUBTIDAL
Oligochaetes
B.
MEAN DENSITY PER CORE (LOGX+1)
1980 1981 1982 1983 1984 1985 1986 1987

Fig. 12. Quarterly means of log-transformed abundance ((LN(X + 1)), multiple regression predictions, and adjusted annual abundances of Millstone subtidal infaunal communities from March 1979 - June 1987. (Annual means were adjusted using analysis of covariance which included abiotic and climatic conditions as covariates. Error bars represent ± 2 SE.)


C.
STATION: INTAKE SUBTIDAL
Oligochaetes
R ² = 0.28
MEAN DENSITY PER CORE (LOG X+1)
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88




D.
STATION: JORDAN COVE SUBTIDAL
Oligochaetes
R ² = 0.36
MEAN DENSITY PER CORE (Log X+1)
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88

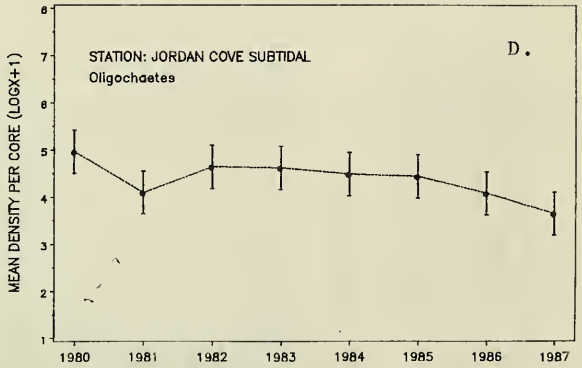


Fig. 12. Continued.

After removing variation attributed to abiotic factors, significant trends over sampling years were evident at EF and GN. At EF, there was a significant increasing trend which principally reflected the low abundances collected in 1980 and 1981. At this station, the 1986 and 1987 means were significantly different from only 1980, when lowest oligochaete densities were found. Abundances at GN, were also lower in earlier sampling periods. Oligochaete densities in 1986 and 1987 were significantly higher than 1983 when historically low densities occurred in 3 of 4 quarters. In addition, the 1986 value was significantly higher than 1984. At JC, the 1986 mean was significantly lower than 1980, while 1987 was significantly lower than 1980 and 1982-1985. Oligochaete densities at IN in 1986 and 1987 were lower than those collected from 1980-83; only the 1987 mean was significantly lower than 1980, 1982, and 1983.

Mediomastus ambiseta

This capitellid polychaete has been reported in areas of environmental stress caused by disturbance or high nutrient input; it is also common in subtidal areas composed of silty sediments (Boesch and Rosenburg 1982) along the entire U.S. east coast. Classified as an 'opportunist', *Mediomastus ambiseta* is capable of large population increases in response to environmental stress associated with oil spills (Grassle and Grassle 1974; Sanders et al. 1980) and organic enrichments (Boesch and Rosenburg 1982).

Mediomastus ambiseta was the most consistently dominant species at all subtidal stations during 1986-87, ranking 1st at GN, IN and JC and 2nd at EF in terms of the 2-year BIV. Quarterly mean abundance (#/core) over the last two years ranged from 25 - 101/core at GN , 7 - 19/core at EF, 8 - 41/core at IN and 21 - 411/core at JC. At all stations but IN, the abundance of this species dramatically increased in September 1983 and generally remained at high levels through 1987. Over 1986-87, only June 1986 density at JC exceeded the range of previous years' values.

Multiple regression analyses revealed significant increases in the density of this species at all stations. Annual abundance of *Mediomastus ambiseta* peaked in 1984 at JC, EF and GN and remained high through 1987 (Fig. 12 E-H). At IN, highest annual abundance occurred in 1987. Results of pair-wise comparisons between years (t-tests) were as follows: at JC, 1986 and 1987 were significantly higher than 1981-1983. The 1986 and 1987 annual means were significantly higher than all previous years at EF (except 1986 vs 1985 at EF), GN (except for 1987 vs. 1984) and IN.

Aricidea catherinae

Aricidea catherinae is commonly a member of littoral (Whitlatch 1974; Kinner and Maurer 1978) and offshore (Maurer and Leathem 1980) temperate communities. This species was a dominant component of subtidal communities throughout the baseline period, and in 1986-87, ranked 3rd in terms of 1986-87 BIV at GN and JC (Table 5). At both IN and EF, this species did not rank among the top ten in either 1986 or 1987 despite its high ranking in the 1980-85 period.

Densities of *Aricidea catherinae* during the last two years ranged from 19 - 66/core at GN, 4 - 40/core at JC, 1 - 2/core at at EF and 1 - 4/core at IN (Fig. 12 I-L). At GN and IN, values were within the range of those obtained during the pre-operational period (NUSCO 1987). However, at both EF and JC, values since March 1986 (December 1985 at EF) were lower than those found in previous years.

Regression analysis revealed significant differences in the abundance of this species at all stations. At EF, annual densities in 1986 and 1987 were significantly lower than 1980-1984. At JC, both 1986 and 1987 were significantly lower than 1981 (also 1986 vs 1983 and 1984). Abundance of this species at GN and IN was less variable and few significant differences among years were evident. At IN, the 1987 annual density was significantly higher than 1984, while at GN the 1987

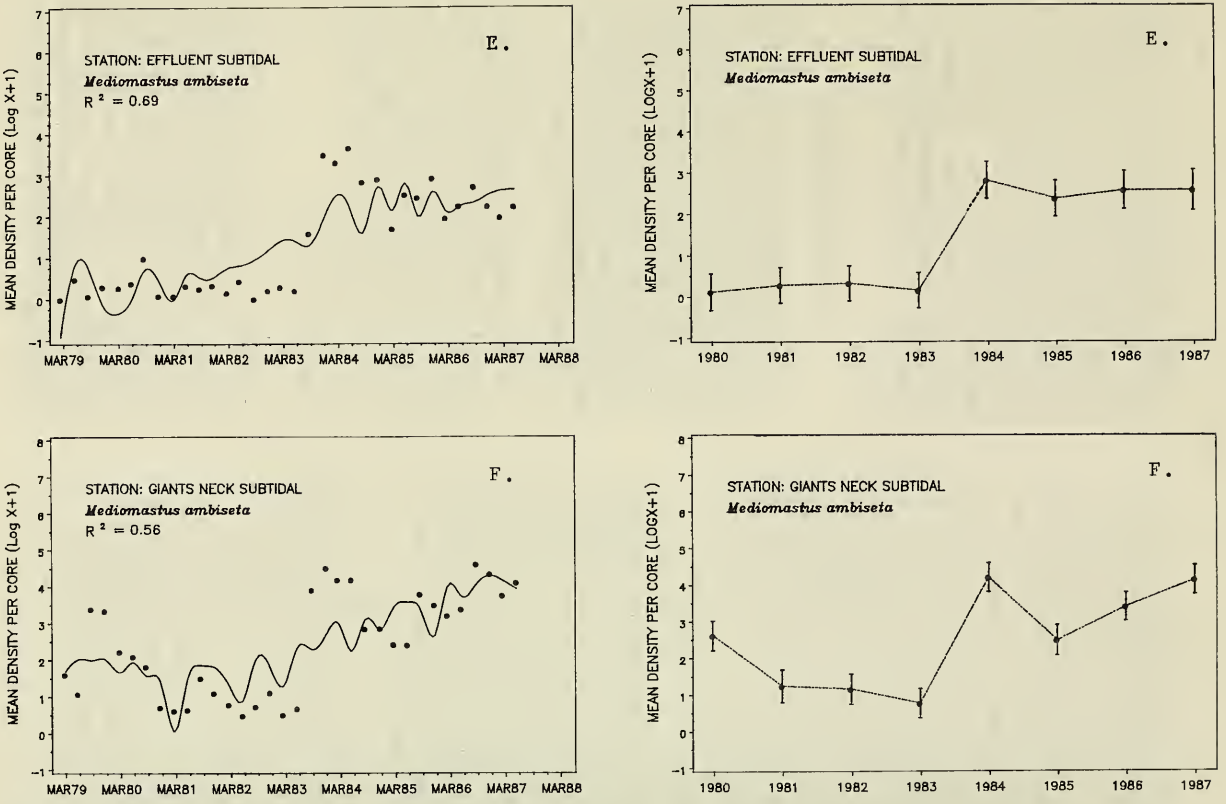
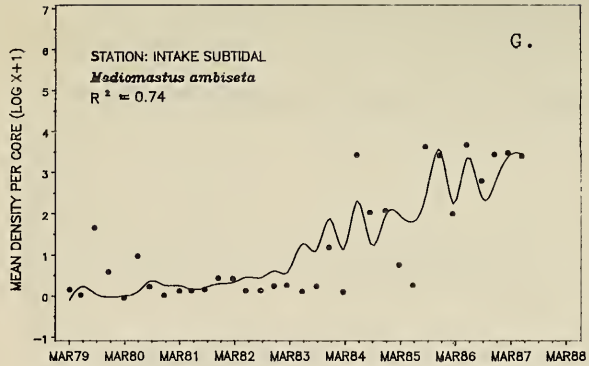
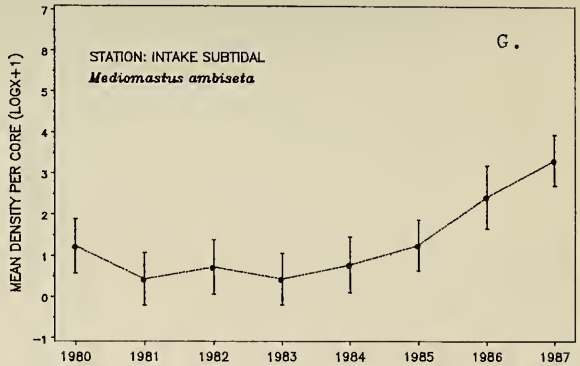
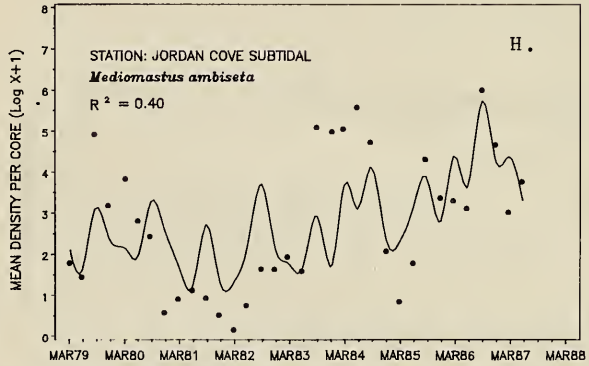

E.
STATION: EFFLUENT SUBTIDAL
Mediomastus ambiseta
R ² = 0.69
MEAN DENSITY PER CORE (Log X+1)
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88
E.
STATION: EFFLUENT SUBTIDAL
Mediomastus ambiseta
MEAN DENSITY PER CORE (LOGX+1)
1980 1981 1982 1983 1984 1985 1986 1987
F.
STATION: GIANTS NECK SUBTIDAL
Mediomastus ambiseta
R ² = 0.56
MEAN DENSITY PER CORE (Log X+1)
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88
F.
STATION: GIANTS NECK SUBTIDAL
Mediomastus ambiseta
MEAN DENSITY PER CORE (LOGX+1)
1980 1981 1982 1983 1984 1985 1986 1987

Fig. 12. Continued.


G.
STATION: INTAKE SUBTIDAL
Mediomastus ambiseta
R ² = 0.74
MEAN DENSITY PER CORE (LOG X+1)
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88




H.
STATION: JORDAN COVE SUBTIDAL
Mediomastus ambiseta
R ² = 0.40
MEAN DENSITY PER CORE (Log X+1)
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88

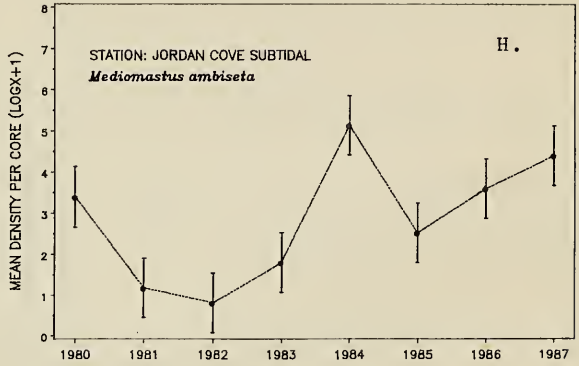

H.
STATION: JORDAN COVE SUBTIDAL
Mediomastus ambiseta
MEAN DENSITY PER CORE (LOGX+1)
1980 1981 1982 1983 1984 1985 1986 1987

Fig. 12. Continued.

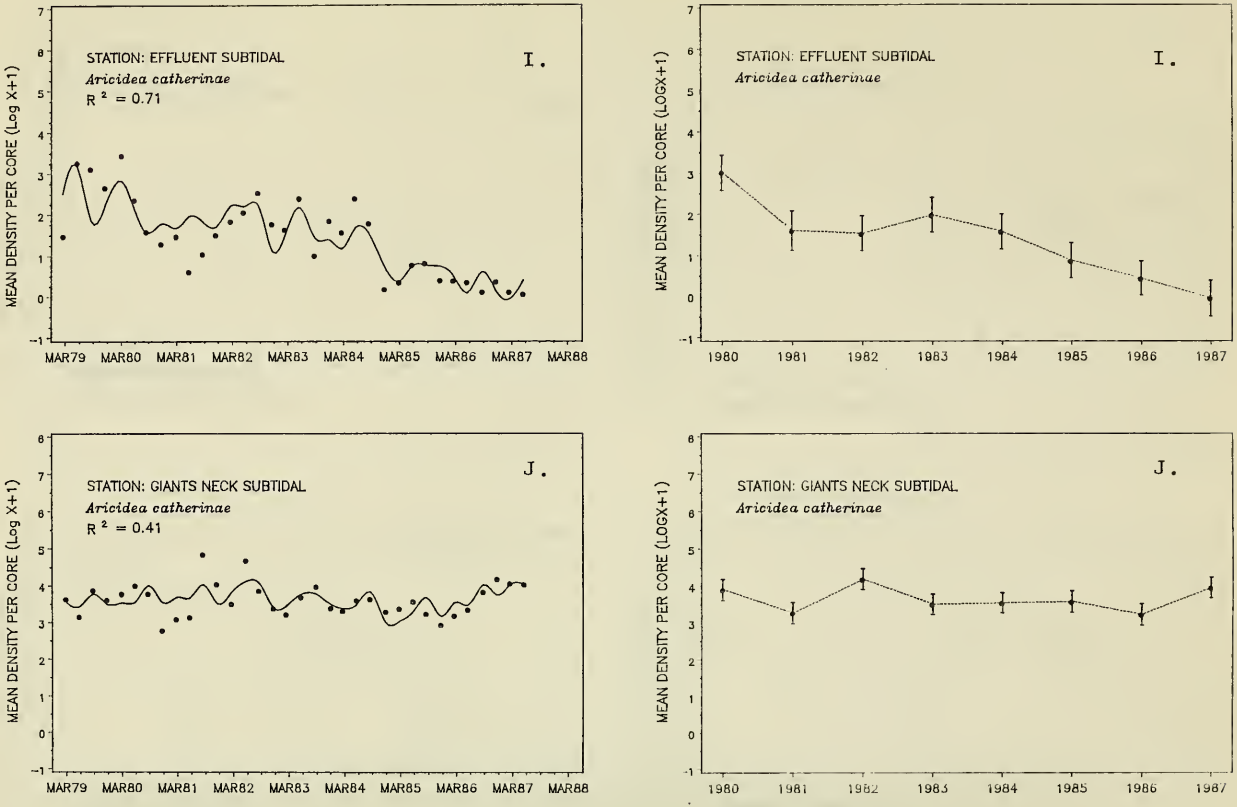

STATION: EFFLUENT SUBTIDAL
Aricidea catherinae
R 2 = 0.71
I.
MEAN DENSITY PER CORE (Log X+1)
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88
STATION: EFFLUENT SUBTIDAL
Aricidea catherinae
I.
MEAN DENSITY PER CORE (LOGX+1)
1980 1981 1982 1983 1984 1985 1986 1987
STATION: GIANTS NECK SUBTIDAL
Aricidea catherinae
R 2 = 0.41
J.
MEAN DENSITY PER CORE (Log X+1)
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88
STATION: GIANTS NECK SUBTIDAL
Aricidea catherinae
J.
MEAN DENSITY PER CORE (LOGX+1)
1980 1981 1982 1983 1984 1985 1986 1987

Fig. 12. Continued.

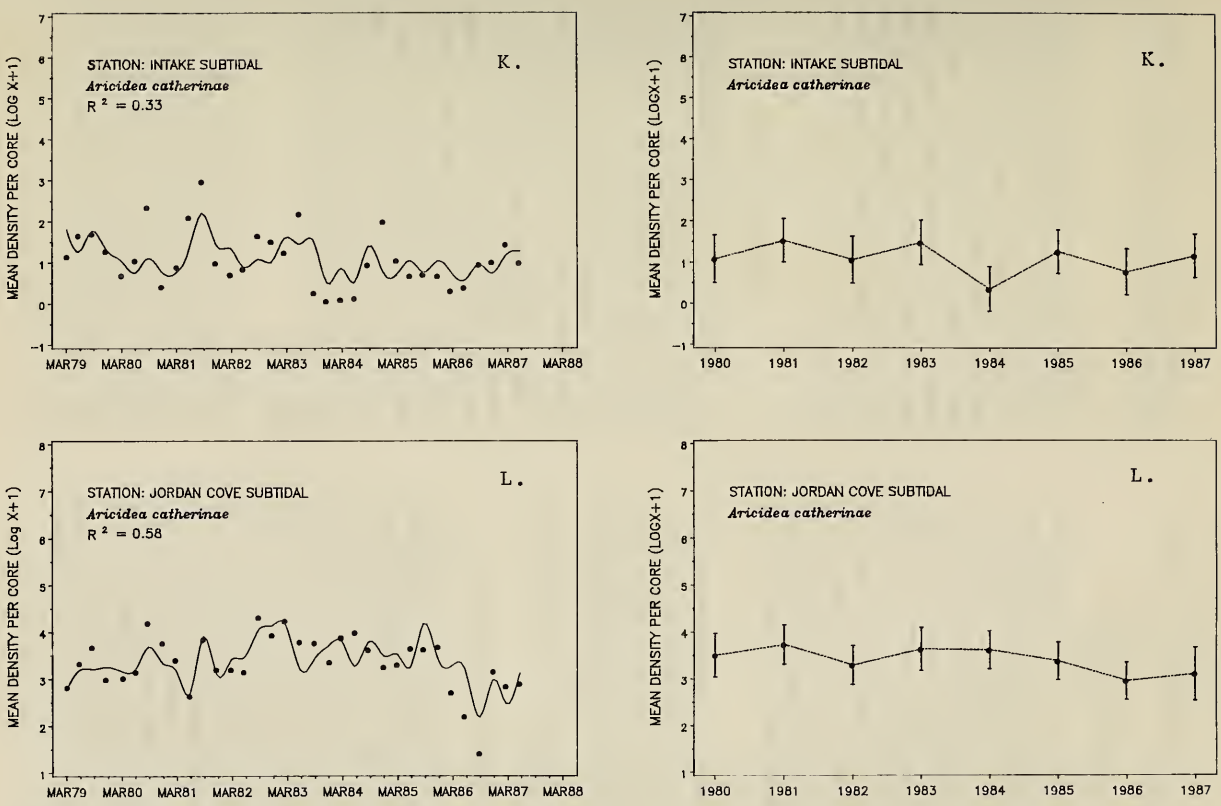

STATION: INTAKE SUBTIDAL
Aricidea catherinae
R 2 = 0.33
K.
MEAN DENSITY PER CORE (LOG X+1)
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88
STATION: INTAKE SUBTIDAL
Aricidea catherinae
K.
MEAN DENSITY PER CORE (LOGX+1)
1980 1981 1982 1983 1984 1985 1986 1987
STATION: JORDAN COVE SUBTIDAL
Aricidea catherinae
R 2 = 0.58
L.
MEAN DENSITY PER CORE (Log X+1)
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88
STATION: JORDAN COVE SUBTIDAL
Aricidea catherinae
L.
MEAN DENSITY PER CORE (LOGX+1)
1980 1981 1982 1983 1984 1985 1986 1987

Fig. 12. Continued.

annual mean was significantly higher than 1981, 1983, 1984 and 1986.

Polycirrus eximius

Polycirrus eximius is a deposit-feeding polychaete common in shallow subtidal marine and brackish temperate zone waters along the east coast (Gosner 1971). *Polycirrus eximius* was among the ten most abundant taxa at EF and JC during 1986-87. Quarterly values at EF ranged from 1 - 7/core and from 2 - 13/core at JC (Fig. 12 M-N) from September 1985 - June 1987. Since December 1985, densities at EF have been well below those obtained in prior sampling periods. Densities at JC were within the range of previous years, although those recorded in September and December 1986 and March 1987 were among the lowest since 1980.

Regression analysis, which removed 68% (EF) and 36% (JC) of the variation over years indicated that decreases in abundances have occurred since 1984 at both stations. At EF, abundances for 1986 and 1987 were significantly lower than 1980, 1981, and 1983-1985. Abundances at JC for 1986 and 1987 were significant lower than 1984, when peak densities occurred.

Protodorvillea gaspeensis

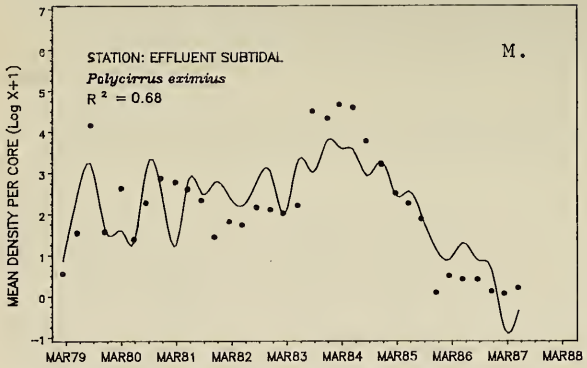
This small motile polychaete is considered a facultative carnivore (Fauchald and Jumars 1979) and common in near-shore sublittoral environments from the Gulf of St. Lawrence to LIS (Pettibone 1963). *Protodorvillea gaspeensis* was a dominant member of the EF community during 1986 and 1987, ranking 3rd in terms of the BIV and 3rd or 4th in terms of average density. This species was also among the dominants at this station from 1980-85, although large year-to-year shifts in abundance occurred. At GN, this species was among the top ten numerical dominants since 1980; however, densities were consistently below 10/core in all but the 1987 sampling period (Fig. 12 O-P). From September 1985 - June 1987, average quarterly abundance of *Protodorvillea gaspeensis* ranged from 3 - 13/core at both stations. All values obtained since September 1985 were within the range of those obtained in past sampling periods.

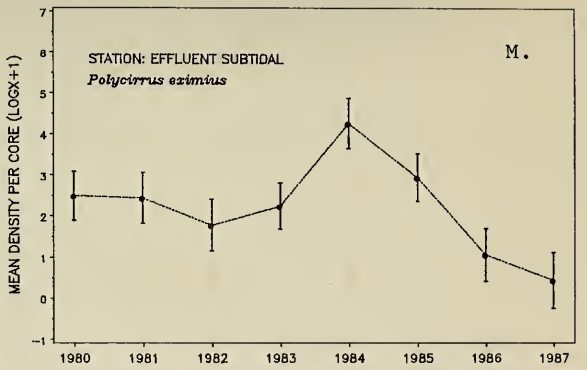
Multiple regression analysis removed 53% and 46% of the variation at EF and GN, respectively, and revealed that significant year-to-year variations occurred at both stations. At GN there has been a significant increasing trend in the abundances of this species since 1980. In addition, densities in 1987 were significantly higher than those obtained from 1980-83. An increasing trend was not evident at EF; where significant differences occurred between the 1980 low and all other years. In addition, 1986 was significantly lower than 1981.

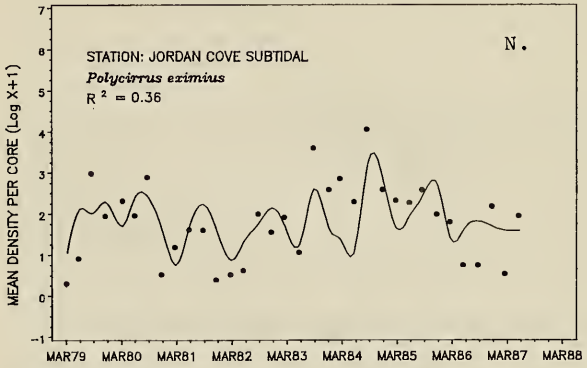
Lumbrineris tenuis

Lumbrineris tenuis is a burrowing deposit-feeding omnivore which can consume a variety of food items ranging from sediments, algae and eelgrass detritus to other infauna (Pettibone 1963). Common in subtidal areas from Maine to the Gulf of Mexico, this species is found in muds, sands and eelgrass beds to depths of 128 fathoms (Pettibone 1963). This species was a consistent dominant at JC during 1986-87 and also during 1980-85. Although this species was less abundant and exhibited large temporal fluctuations at GN, analysis was performed to provide comparison to results obtained at JC. Quarterly densities during the 1986 and 1987 sampling periods ranged from 3 - 18/core at JC and from 4 - 14/core at GN (Fig. 12 Q-R). Values at both stations were within the range of previous years, although March and June 1986 means were among the lowest recorded at this station.

Multiple regression analysis indicated that there were no long-term trends at either station; however, significant interannual differences occurred. At JC, the 1987 mean was significantly higher than 1983; also 1986 was significantly lower than 1984. Annual abundances were less variable at GN and 1986 and 1987 were significant from only 1980 and 1981.


STATION: EFFLUENT SUBTIDAL
Polycirrus eximius
R ² = 0.68
M.
MEAN DENSITY PER CORE (Log X+1)
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88




STATION: JORDAN COVE SUBTIDAL
Polycirrus eximius
R ² = 0.36
N.
MEAN DENSITY PER CORE (Log X+1)
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88

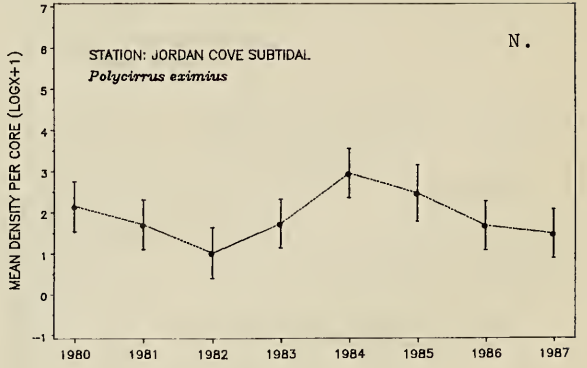


Fig. 12. Continued.

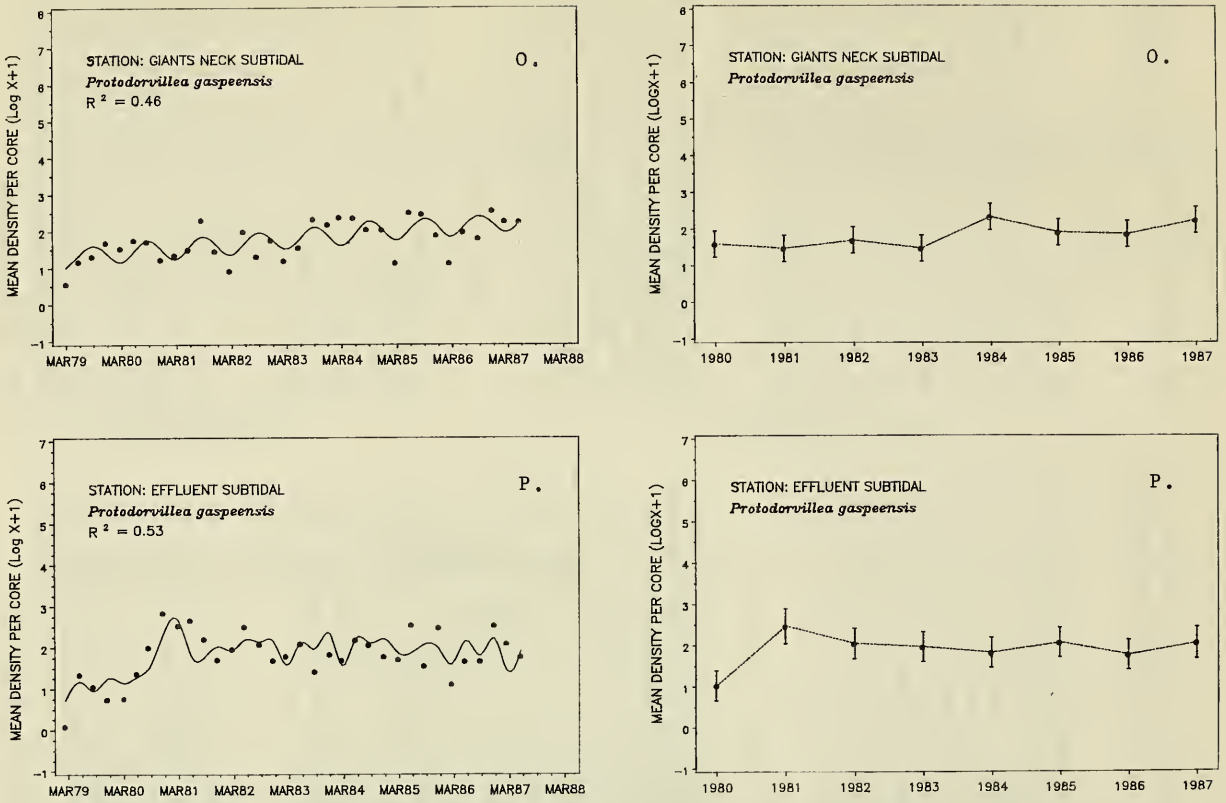

STATION: GIANTS NECK SUBTIDAL
Protodorvillea gaspeensis
R 2 = 0.46
O.
MEAN DENSITY PER CORE (Log X+1)
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88
STATION: GIANTS NECK SUBTIDAL
Protodorvillea gaspeensis
O.
MEAN DENSITY PER CORE (LOGX+1)
1980 1981 1982 1983 1984 1985 1986 1987
STATION: EFFLUENT SUBTIDAL
Protodorvillea gaspeensis
R 2 = 0.53
P.
MEAN DENSITY PER CORE (Log X+1)
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88
STATION: EFFLUENT SUBTIDAL
Protodorvillea gaspeensis
P.
MEAN DENSITY PER CORE (LOGX+1)
1980 1981 1982 1983 1984 1985 1986 1987

Fig. 12. Continued.

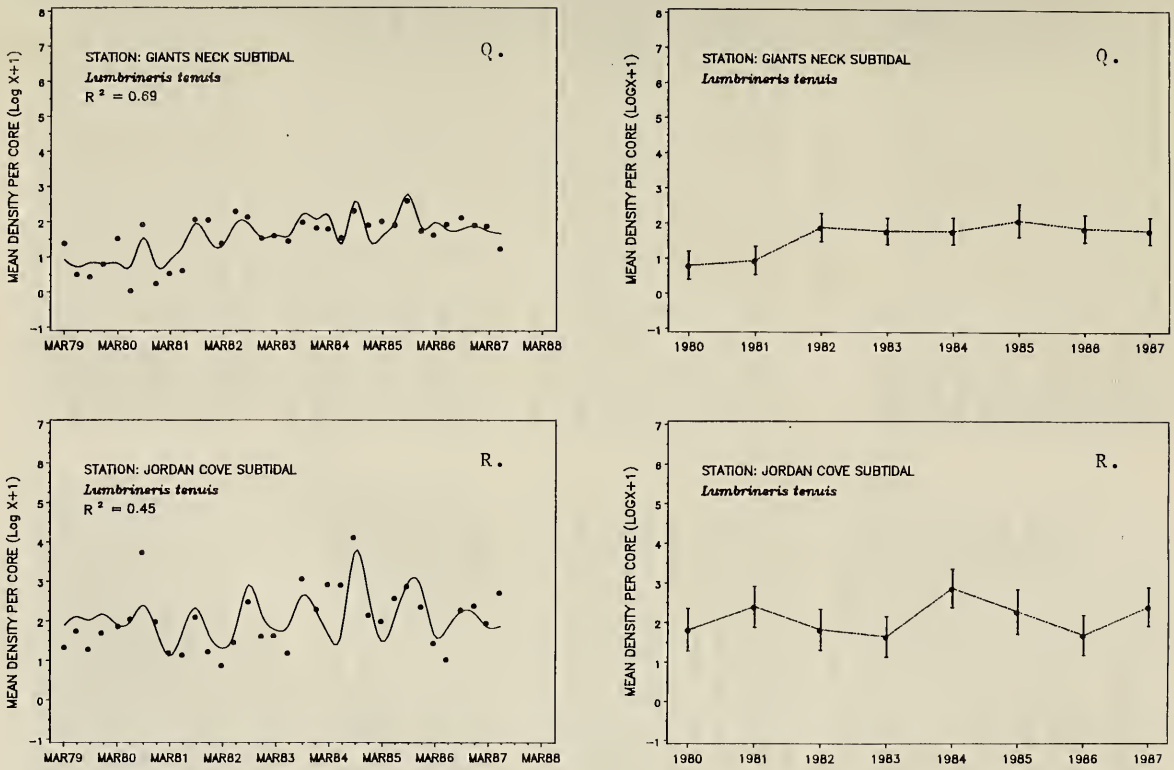

STATION: GIANTS NECK SUBTIDAL
Lumbrineris tenuis
R ² = 0.69
Q.
MEAN DENSITY PER CORE (Log X+1)
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88
STATION: GIANTS NECK SUBTIDAL
Lumbrineris tenuis
Q.
MEAN DENSITY PER CORE (LOGX+1)
1980 1981 1982 1983 1984 1985 1986 1987
STATION: JORDAN COVE SUBTIDAL
Lumbrineris tenuis
R ² = 0.45
R.
MEAN DENSITY PER CORE (Log X+1)
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88
STATION: JORDAN COVE SUBTIDAL
Lumbrineris tenuis
R.
MEAN DENSITY PER CORE (LOGX+1)
1980 1981 1982 1983 1984 1985 1986 1987

Fig. 12. Continued.

Ampelisca spp.

These suspension-feeding amphipods inhabit sediments from fine sands to muds and are common to shallow subtidal communities from the Gulf of St. Lawrence to the Gulf of Mexico. *Ampelisca* spp. (including *Ampelisca abdita*, *A. vadorum*, *A. verrilli*) are common members of topographic depressions of the Middle Atlantic Continental Shelf, and do not enhance materials exchange because they live at the sediment surface and actually tend to reduce sediment resuspension and hence geochemical exchange (Boesch 1979).

Ampelisca spp. were dominant components of the IN community during 1986-87, and were also present in previous years, although densities were typically low (< 10/core) and large year-to-year fluctuations in density were common (low BIV's). In 1986 and 1987, quarterly densities of this taxon ranged from 2 - 228/core (Fig. 12 S). Except for March 1986, abundances over the last two years were consistently higher than those obtained from March 1979 - June 1984 and of similar magnitude to those obtained from September 1984 through June 1985.

Over the eight year sampling period, a significant increasing trend has occurred in the abundance of these species principally due to the large increases observed in each of the last three years. Annual mean abundances in 1986 and 1987 were significantly higher than those obtained from 1980-1984. However, neither year was significantly different from 1985.

Species Diversity

Mean species diversity (H') of subtidal communities during 1986 and 1987 ranged from 2.9 - 4.3, evenness (J) from 0.5 - 0.7 and total number of species (S) from 46 - 82 (Table 6). In both sampling years, highest diversity and evenness and lowest number of individuals were collected at EF. Highest species number occurred at GN in both sampling years.

Species diversity values during 1986 and 1987 generally fell within the range established by previous studies (NUSCO 1987). In 1986 and 1987, diversity was generally lower than 1985, a year during which relatively higher species number and evenness occurred. At three of the monitoring stations (GN, JC, and IN), lower H' and J over the last two years were attributable to the large increase in the abundance of *Mediomastus ambiseta* and *Leptocheirus pinguis*. Diversity at EF was within the range observed in previous years, but density and number of species in 1986 and 1987 were low compared to 1984 and 1985.

Cluster Analysis

Cluster analysis of annual subtidal species abundances (Fig. 13) showed two major station/groups: Group I included all Intake collections and Group II contained all remaining samples. The low similarity of IN to other sampling stations is due to large differences in species composition and abundance. For example, the infaunal communities collected in 1986 and 1987 at IN included high numbers of ampeliscid amphipods, species which are present, but are not usually among the numerical dominants at other stations.

The IN grouping was further divided into a group containing 1984-87 collections and one including 1980-83 collections. This separation reflected a change in the species composition which occurred after 1983. The 1984-87 collections shared similarly high densities of amphipods, molluscs, *Mediomastus ambiseta* and *Owenia fusiformis*, and overall lower numbers of other annelids, particularly oligochaetes.

Group II included all other station/years which separated into spatial groups (Subgroups A, B, C,). The 1986 and 1987 collections at GN, EF and JC formed couplets within each of their respective subgroups which then linked to remaining years. The lower similarity between 1986-87 collections and those of other years reflected not only interannual shifts in population abundance but changes in dominance structure as well.

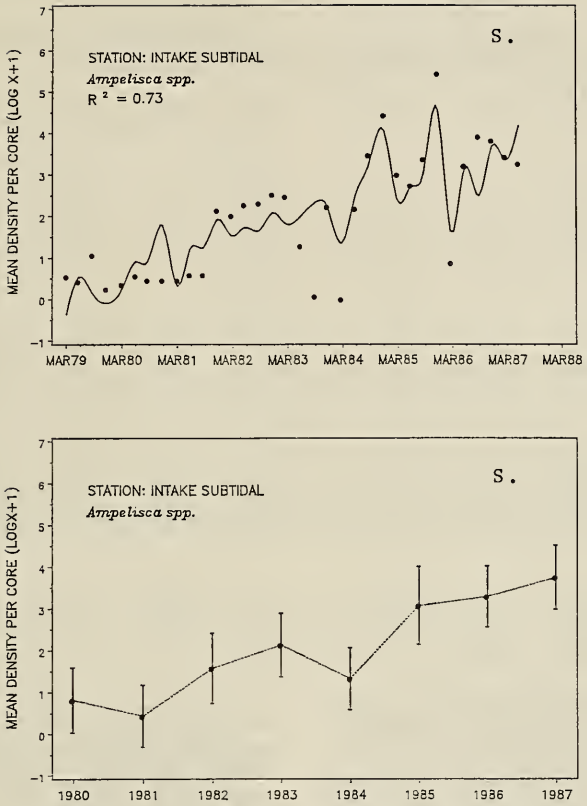

S.
STATION: INTAKE SUBTIDAL
Ampelisca spp.
R 2 = 0.73
MEAN DENSITY PER CORE (LOG X+1)
MAR79 MAR80 MAR81 MAR82 MAR83 MAR84 MAR85 MAR86 MAR87 MAR88
S.
STATION: INTAKE SUBTIDAL
Ampelisca spp.
MEAN DENSITY PER CORE (LOGX+1)
1980 1981 1982 1983 1984 1985 1986 1987

Fig. 12. Continued.

The GN collections in 1986 included higher numbers of *Mediomastus ambiseta*, *Tharyx dorsobranchialis*, *Ampelisca vadorum*, *Ampelisca verrilli* and lower numbers of *Tharyx acutus* and *Polycirrus eximius* than previous years. The 1987 collection also included large numbers of *Leptocheirus pinguis*. At EF, 1986 and 1987 exhibited lower similarity to other years due to the overall decline in the abundance of *Tharyx acutus*, *Polycirrus eximius*, *Aricidea catherinae* and the increase in oligochaetes, *Mytilus edulis*, rhynchocoels and *Owenia fusiformis*. In 1986

samples at JC, lower numbers of *Mediomastus ambiseta*, oligochaetes, *Aricidea catherinae*, *Lumbrineris tenuis* were collected relative to previous years, while in 1987, a large increase in *Mediomastus ambiseta* and *Leptocheirus pinguis* and continued decreases in oligochaetes,

TABLE 6. Annual mean species diversity (H'), evenness (J), species number (S) and total individuals (N) (± 1 standard error) for Millstone subtidal stations September 1979 - June 1987.

STATION	1980	1981	1982	1983	1984	1985	1986	1987
EFFLUENT								
H'	2.7 ± 0.2	3.9 ± 0.3	4.4 ± 0.2	4.6 ± 0.1	3.6 ± 0.2	4.8 ± 0.1	4.3 ± 0.2	4.3 ± 0.2
J	0.4 ± 0.1	0.7 ± 0.1	0.7 ± 0.1	0.7 ± 0.1	0.6 ± 0.1	0.7 ± 0.1	0.7 ± 0.01	0.7 ± 0.01
S	63 ± 6	66 ± 13	63 ± 9	75 ± 8	84 ± 4	86 ± 5	60 ± 6	68 ± 6
N	1583 ± 29	1324 ± 364	689 ± 144	809 ± 88	2333 ± 211	1667 ± 228	778 ± 134	875 ± 153
GIANTS NECK								
H'	3.6 ± 0.1	3.6 ± 0.2	3.4 ± 0.1	3.4 ± 0.1	3.5 ± 0.2	4.2 ± 0.1	3.8 ± 0.1	3.3 ± 0.1
J	0.6 ± 0.1	0.6 ± 0.1	0.6 ± 0.1	0.6 ± 0.1	0.6 ± 0.1	0.6 ± 0.1	0.6 ± 0.02	0.5 ± 0.02
S	68 ± 4	57 ± 10	69 ± 6	53 ± 5	73 ± 8	82 ± 4	82 ± 4	74 ± 10
N	2080 ± 46	1177 ± 394	1975 ± 456	1230 ± 175	2549 ± 217	1824 ± 281	1994 ± 279	2826 ± 419
INTAKE								
H'	4.1 ± 0.1	3.8 ± 0.1	3.9 ± 0.1	3.4 ± 0.3	3.4 ± 0.2	3.8 ± 0.3	3.0 ± 0.4	3.2 ± 0.3
J	0.8 ± 0.1	0.7 ± 0.1	0.7 ± 0.1	0.7 ± 0.1	0.7 ± 0.1	0.7 ± 0.1	0.6 ± 0.1	0.5 ± 0.1
S	44 ± 4	37 ± 6	45 ± 3	37 ± 3	30 ± 8	51 ± 3	46 ± 3	60 ± 3
N	389 ± 797	301 ± 102	474 ± 71	369 ± 81	445 ± 335	907 ± 293	1392 ± 589	2790 ± 921
JORDAN COVE								
H'	3.6 ± 0.2	3.7 ± 0.4	3.0 ± 0.4	3.0 ± 0.2	2.6 ± 0.2	3.8 ± 0.2	3.6 ± 0.1	2.9 ± 0.5
J	0.7 ± 0.1	0.6 ± 0.1	0.6 ± 0.1	0.5 ± 0.1	0.4 ± 0.1	0.6 ± 0.1	0.6 ± 0.01	0.5 ± 0.1
S	66 ± 1	66 ± 9	44 ± 6	55 ± 4	67 ± 9	72 ± 9	68 ± 10	70 ± 5
N	1694 ± 480	1202 ± 449	724 ± 145	1477 ± 174	3561 ± 523	1949 ± 711	1489 ± 354	3455 ± 890

Aricidea catherinae, and *Polycirrus eximius* occurred.

Discussion

The most immediate environmental impacts associated with Unit 3 start-up were attributable to the increased volume of cooling water discharge and to sedimentary changes caused by the scouring action of the discharge. Infaunal community changes that might have been related to elevated temperatures could not be distinguished from those due to sediment shifts which occurred after start-up. The progression in sediments below the discharge from medium sands to coarse gravels, to cohesive clays (glacial lake bed deposits) and finally to bedrock was similar to that observed by Saenger et al. (1982) and in Maine following power plant start-up (Maine Yankee Atomic Power Co. 1978).

The EF station, located approximately 100 m offshore, was subjected to less severe scour than areas immediately below the discharge; however, plant-induced scour and sedimentary changes (increased grain size and decreased silt/clay content) were evident after Unit 3 start-up. Along with

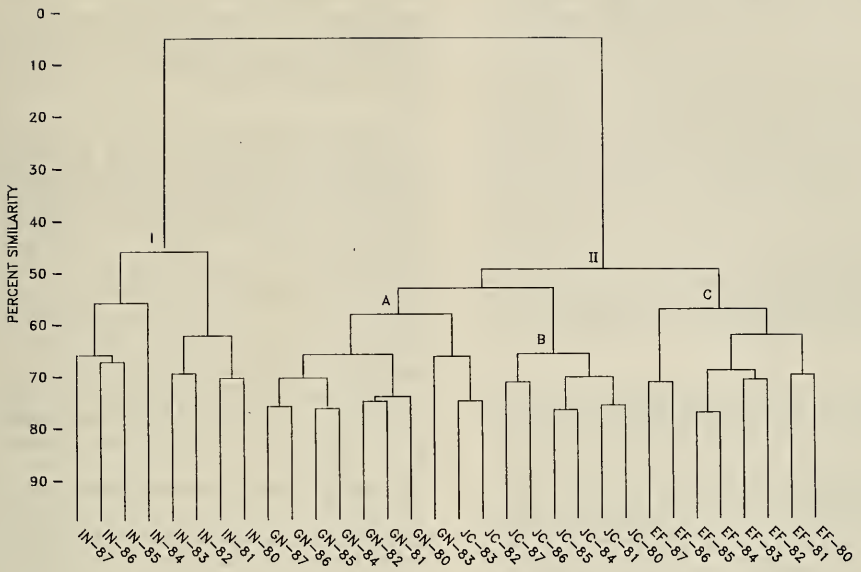


Fig. 13. Dendrogram resulting from the classification of annual subtidal collections at Millstone subtidal stations September 1979 - June 1987.

sedimentary changes at EF, we observed reductions in macrofaunal density and species number. The reduced species richness ended the increasing trend evident at this station since 1980. There was also a trend for lowered abundances of *Polycirrus eximius*, *Aricidea catherinae*, oligochaetes, *Tellina agilis*, *Tharyx* spp. and *Lumbrineris tenuis*. These deposit-feeding species became abundant during 1984 and 1985 following an increase in silt/clay due to construction of the Unit 3 Intake structure and to the completion of the Unit 3 discharge cut (NUSCO 1987).

Power plant-related impacts were also evident at JC after 3-unit start-up and were evidenced by both sedimentary and infaunal community changes. Increased silt/clay content was observed at this station in September 1986, and was probably due to the transport and settling of sediments scoured from area of the Unit 3 discharge cut. Although the Unit 3 discharge cut was completed in August 1984, the bottom area was not subjected to scour until April 1986, when 3-unit operation began.

Concurrent with sediment changes at JC, there was a significant increase in the abundance of *Mediomastus ambiseta* along with a decline in the abundance of many polychaetes and oligochaetes. Although higher densities of *Mediomastus ambiseta*, were apparent at other stations during the operational period, increased dominance by

this species was probably enhanced by the higher silt/clay content, given its affinity for inhabiting silty areas that have been recently disturbed (e.g., Boesch 1982; Sanders et al. 1972). Abundances of other species, including *Aricidea catherinae* and *Polycirrus eximius*, significantly declined following siltation of JC. As mentioned previously, these organisms are deposit-feeders and thus their decline was probably not food-related. However, since they feed near the sediment surface they might be subject to burial. In addition, high sediment load can cause direct mortality in resident populations (Turk and Risk 1981). Changes in sediment parameters similar to those evident after start-up of Millstone Unit 3 have been observed at other power stations (Dean and Ewart 1978; Saenger et al. 1980)

The IN area also exhibited changes in sediments and infaunal communities during the operational period. Silt/clay values during 1987 were generally lower than those in recent years, but similar to values obtained prior to 1984 (NUSCO 1987). The infaunal community in 1987 exhibited significant increases in the abundances of the amphipods, *Ampelisca* spp., *Leptocheirus pinguis* and *Uniciola irrorata*. These organisms were among the dominants at IN prior to the construction activities and are the 'background' components of the *Nucula-Nepthys* community found in Niantic Bay, the area adjacent to the IN station (NUSCO 1980).

Prior to Unit 3 construction activities, IN was characterized as a dynamic area subjected to strong tidal currents, and the infaunal communities were dominated by suspension-feeding arthropods (NUSCO 1984). Since then, construction impacts (see NUSCO 1987 for summary) have been evidenced by increased silt/clay content and reductions in infaunal abundance and number of species and the increased dominance of opportunistic deposit-feeding polychaetes such as *Polydora ligni*, *Capitella* spp. and *Mediomastus ambiseta*, which become abundant following stress (Grassle and Grassle 1974; McCall 1977; Swartz et al. 1980; Flint and Younk 1983; Nichols 1985). A reduction in silt/clay content in 1987 may have been a response to increased currents produced by start-up and continuous operation of Unit 3 circulating water pumps. The return to an amphipod-dominated community at IN is believed indicative of recovery from plant-related impacts which occurred in previous years.

Power plant-related impacts during the first year of 3-unit operation appeared most related to scouring (at EF and IN) and to the transport and deposition of this sediment into JC. Infaunal habitats immediately beneath the Unit 3 cut have been eliminated due to scouring by the 3-unit discharge; however, given the limited size of the area, loss of this habitat would not significantly alter ecosystem functioning in the greater Millstone area. At JC, the deposition of sediments apparently from the discharge area would be expected as a temporary change. Once all available sediment is scoured from the EF area, no additional siltation of JC should occur. Infaunal changes related to this siltation should also be temporary and cause no detectable changes in the ecology of the Millstone area. If however, the sedimentary changes are the result of some plant-induced change in the sedimentation patterns in JC or the infaunal shifts were a response to temperature, then more widespread and ecologically significant changes in local infaunal communities might occur. These possible impacts can not be addressed until a more comprehensive operational database is established.

Conclusions

Subtidal infaunal communities exhibited changes in abundance, number of species and population abundances following start-up of Millstone Unit 3. Infaunal changes appeared most related to shifts in sedimentary characteristics attributed to scouring in the Unit 3 intake and discharge areas and to transport of these sediments to adjacent subtidal areas. Changes which might have been mediated by increased water temperature could not be identified separately from power plant-induced sediment changes.

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Lobster Population Dynamics

Introduction

The American lobster, *Homarus americanus*, is the most valuable commercial species in Long Island Sound (LIS) (Blake and Smith 1984). Commercial landings of 1.57 and 2.03 million pounds in 1986 and 1987, respectively, were valued in excess of 5 million dollars. The proportion of the total catch landed in New London county, which includes the Millstone Point area, was 27% in both years (CT DEP Marine Fishery Statistics for 1986 and 1987). Because lobsters are an important commercial resource in the Millstone Point area, dynamics of the local lobster population have been studied to determine if construction and operation of the Millstone Nuclear Power Station (MNPS) have caused changes in the local population beyond those expected from natural variation.

Potential effects of MNPS operations on the lobster population are entrainment of larvae through the cooling water systems, impingement of lobsters on the intake traveling screens, thermal effects of the discharge and disruption of lobster habitat caused by routine dredging in the vicinity of the intakes. While mortality due to entrainment and impingement may alter recruitment patterns of lobsters by reducing the survival of lobster larvae and juveniles, the thermal plume may affect the behavior of adults which may result in a decline in the local inshore fishery. Dredging may temporarily disrupt lobster habitat (shelters) and thereby displace lobsters from the affected area until sediments stabilize.

The lobster studies at MNPS were designed to evaluate year-to-year, seasonal, and between station changes in catch per unit effort and in population characteristics such as size frequency, growth rate, sex ratio, female size at sexual maturity, characteristics of egg-bearing females and lobster movements. Lobster larvae studies were conducted to assess potential impacts of entrainment on the larval stage of lobsters. The results of these studies are compared to other studies conducted throughout the range of the American lobster.

In order to assess potential impacts on the local lobster population associated with 3-unit operation, this report compares data collected during 3-unit operation (1986-87) to data collected before Unit 3 became operational.

Materials and Methods

A detailed description of methods used to conduct lobster population studies from 1969 to 1985 can be found in NUSCO (1987a). Since 1978, four pot trawls consisting of five double entry wire pots (76x51x30 cm; 2.5 cm^2 mesh) equally spaced along a 50-75 m line bouyed at both ends were used to collect lobsters from May through October at three stations (Jordan Cove, Intake, and Twotree; Fig. 1). Pots were individually numbered beginning in 1984 to determine the variability in catch among pots, and provided more accurate values for catch-per-pot than an average catch-per-pot based on the 20 pots of each sampling location. Pots were checked three times each week, rebaited with flounder carcasses and reset in the same area. Lobsters > 55 mm carapace length were banded to restrain chelipeds, brought to the lab, and kept in a tank supplied with a continuous flow of seawater. On Fridays, lobsters caught that week were examined and the following data were recorded: sex, presence of eggs (berried), carapace length (CL), crusher claw position, missing claws and molt stage (Aiken 1973). Lobsters were then tagged with a serially numbered international orange sphyrion tag (Scarratt and Elson 1965; Scarratt 1970), and released at the site of capture. Recaptured tagged

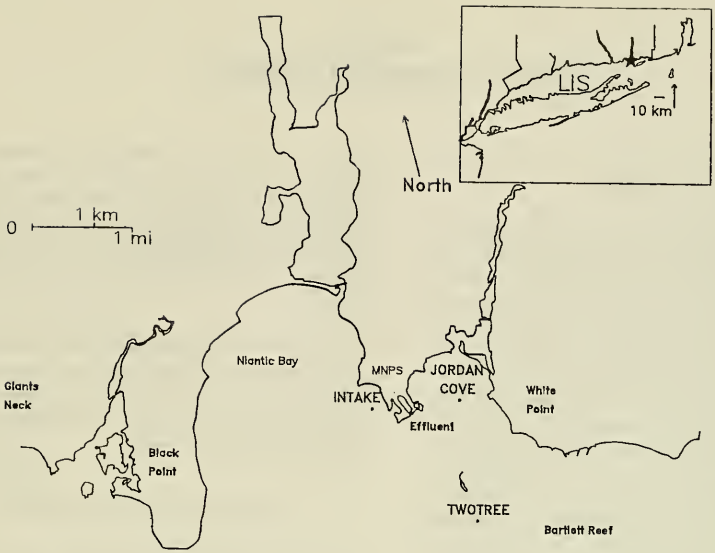

Fig. 1. Location of the Millstone Nuclear Power Station (MNPS) and the three lobster sampling stations (•).

lobsters, severely injured or newly molted (soft) lobsters, and those < 55 mm CL were released untagged after recording the above data.

Beginning in 1981, data were collected to determine the size at which females become sexually mature by measuring the maximum outside width of the second abdominal segment of all females to the nearest millimeter. Female size at sexual maturity was estimated by calculating the ratio of the abdominal width to the carapace length and plotting that ratio against the carapace length (Skud and Perkins 1969; Krouse 1973).

Catch per unit effort (CPUE), calculated as the number of lobsters caught per pothaul was averaged by computing the arithmetic mean. Because the CPUE data are ratios, they are not additive and have an asymmetric distribution about the arithmetic mean. Therefore, we computed the geometric mean which is the best statistic for constructing asymmetric confidence intervals for log-normal data (Snedecor and Cochran 1967). Since 1984, in addition to counting the number of lobsters caught in each pot we counted the number of other organisms caught, to examine the influence of competing species on lobster catch. The amount of time between pothauls (soaktime or set-over-days) also influences lobster catch, and CPUE data are weighted to account for varying soaktimes. As a result, catch per unit effort was adjusted by covariance analysis for the effect of soaktime and the catch of competing species that significantly affected CPUE.

Methods for the collection of lobsters on the intake traveling screens are described in the Fish Ecology section of this report under Methods and Materials-Impingement. In December 1987, based on historical impingement data collected since 1972, NUSCO and the CT DEP agreed to

TABLE 1. Catch statistics for lobsters caught in pots from May through October (1978-87).

	Total Caught	Number Tagged	Number Recaptured	Pots Hauled	Total CPUE	Percent Recaptured
1978	3578	2768	521	4232	0.85	18.8
1979	5037	3732	722	4086	1.23	19.4
1980	4268	3634	522	4182	1.02	14.4
1981	5110	4246	704	4375	1.17	16.6
1982	9109	7575	1278	4340	2.10	16.9
1983	6376	5160	936	4285	1.49	18.1
1984	7587	5992	1431	4550	1.67	23.9
1985	7014	5609	1235	4467	1.57	22.0
1986	7211	5740	1204	4243	1.70	21.0
1987	7280	5681	1356	4233	1.72	23.9

discontinue impingement monitoring at Unit 2 (NUSCO 1988).

Lobster larvae were sampled from 1984 to 1987 during their period of occurrence (May through July) at Units 1 and 2 discharges. Sampling was not conducted at Unit 3 because of design problems with the gantry system used to collect samples at the Unit 3 outfall. Cooling water flows for combined 3-unit operation were used for calculating total entrainment estimates for the larval season. Samples were collected with a 1.0 x 6.0 m conical plankton net of 1.0 mm mesh. Sample volumes were averaged from those calculated from four General Oceanic flowmeters; about 4000 m^3 of cooling water was filtered in each sample by deploying the net for 45-60 minutes. Four day and four night samples were collected weekly (1 day, 1 night on each of 4 days). Each sample was placed in a large 1.0 mm mesh sieve and kept in tanks supplied with a continuous flow of seawater. Samples were sorted shortly after collection in a white enamel pan and larvae were examined for movement and classified as either live or dead. Lobster larvae were also classified by stage according to the criteria established by Herrick (1911).

Results and Discussion

Abundance and Catch Per Unit Effort

The total numbers of lobster caught during 1986 and 1987 were 7,211 and 7,280, respectively, and both were within the range of values reported since 1978 (Table 1). Total catch per unit effort values for 1986 (1.70) and 1987 (1.72) were also within the range of wire pot values (0.85-2.10). The lower number caught and smaller total CPUE from 1978-81 was due to the use of wood pots (NUSCO 1987a). In wood pots, lobsters were more vulnerable to capture at sizes greater than 76 mm and in wire pots at sizes greater than 70 mm (Keser et al. 1983). The performance of wood and wire pots was evaluated (NUSCO 1987a) and provided the basis for using wire pots exclusively in our studies.

Figure 2 presents geometric mean CPUE for all sizes and legal-sized lobsters caught from 1978 to 1987. The total catch mean CPUE for 1986 and 1987 (1.585, 1.633) was within the range of values reported from 1978 to 1985 (0.904-2.006). No significant trends were identified for total CPUE (test for significance of slopes; $r = 0.25$, $p = 0.48$),

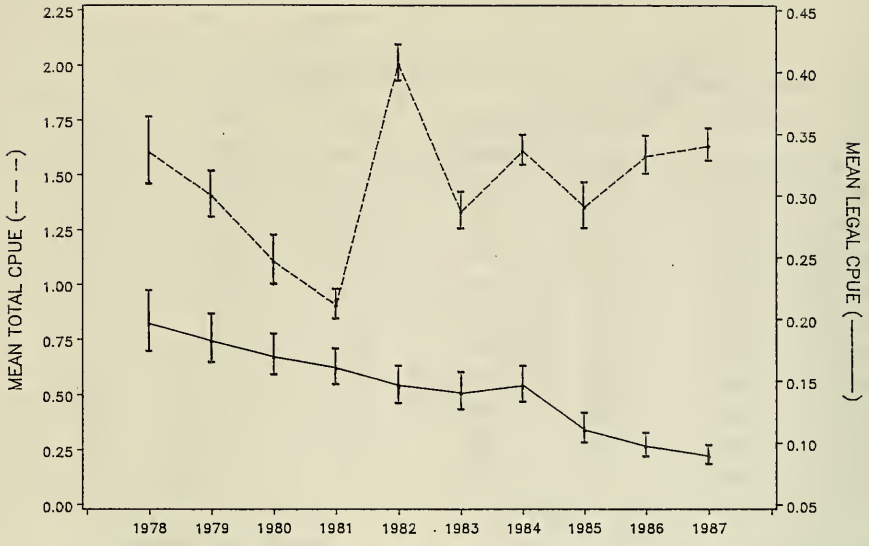

Fig. 2. CPUE geometric means with 95% C.I. for all sizes and only legal size lobsters caught in wire pots from 1978 through 1987.

however, the legal CPUE has steadily declined from 0.196 in 1978 to 0.089 in 1987 ($r = 0.98$, $p < 0.05$). This decline is most likely due to an increase in fishing pressure in LIS. Over 90% of legal-size lobsters in our catch were recruited from sublegal-size classes. Increased fishing pressure on lobsters in NY and CT waters was recently reported by Colvin (1987) and Smith (1987).

The variation in monthly CPUE values during 1986 and 1987 was typical of the seasonal abundance of lobsters (Table 2). The increase in CPUE during the spring and early summer months (May-July) was related to the seasonal variation in water temperature, because lobster activity (e.g., feeding, movement, and molting) is at a maximum after water temperatures rise above 10 °C (McLeese and Wilder 1958; Dow 1966, 1969, 1976; Flowers and Saila 1972). A 50% decline in total CPUE at Jordan Cove from August to September 1986 represented the greatest monthly decline in CPUE at any station since the study began and it was related to scouring at the discharge due to 3-unit operation. Beginning in August 1986, a fine silt material covered traps and lobster shelters in Jordan Cove (500 m from discharge). Analysis of sediment samples collected at the Jordan Cove and Effluent subtidal sand stations indicated changes in sediment composition during the same period (see Benthic Infauna section). SCUBA surveys of the discharge area revealed that fine sediment had been scoured during a period of 3-unit simultaneous operation (May-August 1986). The decline in lobster catches from August (351 lobsters) to September (165 lobsters) was temporary, and catches increased in October and continued to be normal through 1987, indicating that sediments in Jordan Cove had stabilized. A similar short-term impact associated with the disruption of lobster habitat

TABLE 2. Monthly catch statistics for lobsters caught at each station during 1986 and 1987.

1986

Month	Number of pots hauled	Total number caught	Mean CPUE Arithmetic	Mean CPUE Adjusted[a]	Total legals caught	Legal CPUE
			JORDAN COVE			
MAY	217	466	2.11	2.09	9	0.04
JUN	260	568	2.19	2.20	32	0.12
JUL	240	501	2.03	2.03	17	0.07
AUG	238	351	1.47	1.48	13	0.06
SEP	220	165	0.75	0.75	11	0.05
OCT	220	218	0.99	0.99	7	0.03
			INTAKE			
MAY	219	343	1.56	1.79	6	0.03
JUN	260	538	2.05	2.07	29	0.11
JUL	240	448	1.87	1.87	21	0.09
AUG	240	381	1.59	1.52	16	0.07
SEP	220	264	1.20	1.10	18	0.08
OCT	218	239	1.09	1.01	13	0.06
			TWOTREE			
MAY	220	477	2.16	2.21	24	0.11
JUN	260	594	2.35	2.34	36	0.14
JUL	240	518	2.19	2.19	46	0.19
AUG	240	445	1.84	1.79	33	0.14
SEP	220	309	1.41	1.42	11	0.05
OCT	216	330	1.50	1.51	18	0.08

1987

Month	Number of pots hauled	Total number caught	Mean CPUE Arithmetic	Mean CPUE Adjusted[a]	Total legals caught	Legal CPUE
			JORDAN COVE			
MAY	220	387	1.76	1.76	16	0.07
JUN	257	493	1.89	1.89	20	0.08
JUL	260	458	1.76	1.76	33	0.08
AUG	240	346	1.44	1.44	12	0.05
SEP	220	250	1.14	1.14	10	0.05
OCT	219	262	1.19	1.19	7	0.03
			INTAKE			
MAY	219	329	1.51	1.58	14	0.06
JUN	260	420	1.58	1.63	30	0.12
JUL	259	425	1.64	1.63	25	0.10
AUG	240	295	1.22	1.14	14	0.06
SEP	220	308	1.40	1.32	17	0.08
OCT	215	228	1.04	1.10	7	0.03
			TWOTREE			
MAY	215	438	1.99	2.00	17	0.08
JUN	260	662	2.48	2.47	27	0.10
JUL	256	640	2.55	2.54	36	0.14
AUG	240	465	1.94	1.94	29	0.12
SEP	214	439	2.00	2.00	20	0.09
OCT	219	435	1.98	1.98	16	0.07

[a] CPUE values adjusted for the significant effects of soaktime, and the incidental catches of competing species presented in Table 3.

was reported at the Intake station following dredging in 1985 (NUSCO 1987a). Dredging in the vicinity of the intake structures removed existing habitat (shelters), and catches at Intake during 1985 were the lowest reported for that station since wire pots were first used. After the dredged area stabilized, lobsters returned to the area and catches at Intake increased in 1986 and 1987. Pottle and Elner (1982) reported that smothering of habitats occupied by juvenile lobsters may result in increased spatial competition among lobsters for shelter in remaining gravel habitats.

In addition to lobsters, trap catches contained several species of vertebrates and invertebrates. In 1984, we began analyzing the effects of these species on lobster catch using covariance analysis (NUSCO 1985). The species caught in pots at each station were initially used as covariates to identify species that significantly ($p < 0.05$) influenced lobster catch (Table 3). During 1986 and 1987, the influence of catches of competing species on lobster CPUE was the same as in previous years. Five species were identified as significantly influencing lobster CPUE (spider crabs, hermit crabs, whelks, summer and winter flounder). The whelk or conch (*Busycon* spp.) was the only species that had a positive influence on lobster catch. Soaktime was another parameter used in the model as a covariate to examine the significance of varying set-over-days on lobster catch at each station. Soaktime had a significant influence on lobster catch only at Intake; during 1986 and 1987, however, soaktime significantly influenced lobster catch at all stations during 1984. Our soaktimes were not very different; the majority of pots were hauled after a two or three day set. Commercial lobstermen, however, vary the number of days between pot hauls to maximize their catch; therefore, catch statistics for the commercial lobster fishery are often based on catch per trap haul set-over-day to account for the variability in soaktime. The average soaktime for the Connecticut fishery has ranged between 3.2 and 4.5 days since 1978, whereas our soaktime averaged between 2.4 and 2.6 days over the same period (CT DEP Marine Fishery Statistics; NUSCO 1987a). The mean CPUE adjusted for the significant covariates (least square means) are presented with its unadjusted arithmetic mean in Table 2 for each station. Given the similarity between the arithmetic and adjusted mean, the incidental catch of competing species and the variability of our soaktimes did not influence the reliability of our CPUE.

Population Characteristics

Size Frequencies

Annual size frequency distributions for male and female lobsters caught in wire pots from 1979 to 1987 are shown in Figure 3. The mean carapace lengths (CL) of lobsters caught during 1986 (70.1mm) and 1987 (70.2mm) were smaller than previous years' range 1978-85 (70.7-71.8mm) (Table 4). When 3 stations were compared, the mean CL's of lobsters caught at Jordan Cove and Intake were within the range of values reported since 1978, however, the mean CL at Twotree during 1986-87 was smaller than previous years (Table 5). From 1978 to 1984, catches at Twotree contained larger lobsters and greater proportions of legal-size lobsters than nearshore catches; since 1985, the mean CL of lobsters and percentage of legals caught at Twotree have been similar to the nearshore stations. The mean size and proportion of legal-size lobsters caught in our studies since 1978 were lower than that reported by other studies in LIS (Smith 1977; Briggs and Mushacke 1979; Marcello et al. 1979).

Sex Ratios

Sex ratios of males to females were 1.0:0.87 and 1.0:0.88 during 1986 and 1987, respectively, which were within the range of values reported in previous years (Table 6). The Twotree catch had a consistently higher proportion of females than Intake and Jordan Cove catches, which contained more males. This trend in sex ratios has been consistent at the three stations since the study began. Smith (1977) found male to female ratios of commercial catches ranging from 1.0:1.06 to 1.0:1.81 in four different areas of LIS, which is similar to ratios at Twotree 1.5 km offshore. Sex

TABLE 3. Total numbers of lobster and incidental catch of other species and the type of influence that competing species had on lobster catches at each station from 1984 to 1987.

	1984	1985	1986	1987
Lobster	7587	7014	7211	7280
Rock crab	391	145	121	37
Jonah crab	74	32	37	71
Spider crab*	3237	1950	1344	1754
Hermit crab*	428	496	435	721
Blue crab	40	21	26	44
Winter flounder*	45	40	19	30
Summer flounder*	60	24	38	35
Skates	15	17	33	14
Oyster toadfish	76	67	58	39
Scup*	27	90	288	169
Cunner	141	207	206	167
Tautog	39	250	196	208
Sea raven	20	19	6	2
Whelks*	66	78	164	132

JORDAN COVE	1984	1985	1986	1987
Spider crab	(+)			
Hermit crab				
Winter flounder		(--)	(--)	
Summer flounder		(--)		
Scup				
Whelks				

INTAKE	1984	1985	1986	1987
Spider crab	(--)		(--)	(--)
Hermit crab				
Winter flounder		(--)	(--)	
Summer flounder			(--)	
Scup				
Whelks				(+)

TWOTREE	1984	1985	1986	1987
Spider crab			(--)	
Hermit crab		(--)		(--)
Winter flounder				
Summer flounder				
Scup		(--)		
Whelks		(+)	(+)	

(*) Species having a significant ($p < 0.05$) effect on CPUE.

(--) Significant ($p < 0.05$) negative or (+) positive effect on CPUE.

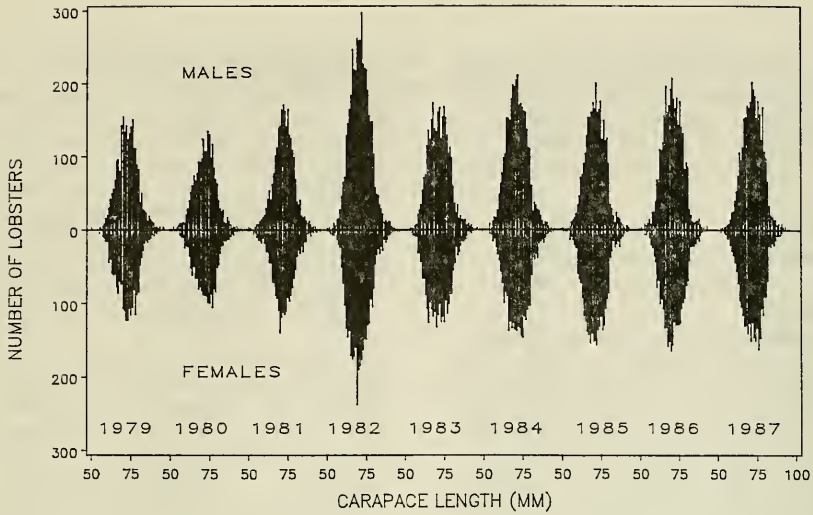

Fig. 3. Size frequency distributions of male and female lobsters caught at all stations from 1979 through 1987.

TABLE 4. Lobster population carapace-length statistics for wire pot catches from May through October 1978-1987.

	N[a]	Range (mm)	Mean Carapace Length ± 95% CI	Percent Legals
1978	1508	53-111	71.4 ± 0.33	8.7
1979	2846	44-100	71.2 ± 0.26	8.2
1980	2531	40-96	70.7 ± 0.27	7.2
1981	1983	43-96	71.0 ± 0.33	9.6
1982	7835	45-103	70.8 ± 0.15	7.3
1983	5432	40-121	71.7 ± 0.19	10.1
1984	6156	45-107	71.8 ± 0.18	9.6
1985	5723	38-101	71.3 ± 0.17	6.6
1986	5961	36-107	70.1 ± 0.17	5.1
1987	5924	36-99	70.2 ± 0.17	4.4

[a] Recaptures not included

TABLE 5. Lobster population carapace-length statistics for wire pot catches at each station from May through October 1978-1987.

JORDAN COVE	N[a]	Range (mm)	Mean Carapace Length ± 95% CI	Percent Legals
1978	489	54-111	70.3 ± 0.54	4.9
1979	1138	46-96	70.7 ± 0.39	7.6
1980	831	40-93	70.2 ± 0.45	5.2
1981	556	45-93	70.6 ± 0.64	7.7
1982	2323	49-96	69.8 ± 0.26	5.1
1983	1965	40-100	71.0 ± 0.32	9.0
1984	1999	52-107	70.7 ± 0.29	6.7
1985	1722	48-96	71.1 ± 0.32	6.4
1986	1748	38-99	69.8 ± 0.31	4.0
1987	1690	44-95	70.2 ± 0.32	4.1
INTAKE				
1978	645	55-110	71.8 ± 0.50	10.4
1979	1087	50-100	71.4 ± 0.41	8.3
1980	855	46-95	70.6 ± 0.45	6.2
1981	686	43-95	69.2 ± 0.53	5.0
1982	2402	51-103	70.2 ± 0.27	5.8
1983	1436	52-110	71.2 ± 0.37	7.5
1984	1830	45-105	70.5 ± 0.32	6.7
1985	1215	44-99	71.2 ± 0.37	6.0
1986	1888	50-107	69.3 ± 0.31	4.9
1987	1687	47-94	70.2 ± 0.32	5.2
TWOTREE				
1978	374	53-94	72.2 ± 0.67	10.7
1979	621	44-94	71.8 ± 0.58	9.3
1980	845	40-96	71.3 ± 0.49	10.1
1981	741	48-96	73.0 ± 0.54	15.3
1982	3110	45-102	72.0 ± 0.25	10.2
1983	2031	43-121	72.8 ± 0.32	12.9
1984	2327	50-105	73.7 ± 0.29	14.4
1985	2786	38-101	71.5 ± 0.25	7.1
1986	2325	36-97	71.0 ± 0.27	6.1
1987	2547	36-99	70.2 ± 0.27	4.1

[a] Recaptures not included

TABLE 6. Male to female sex ratios of lobsters caught in wire pots from May to October, 1978 to 1987.

	Jordan Cove	Intake	Twotree	All Stations
1978	1.0 : 0.79	1.0 : 0.97	1.0 : 1.02	1.0 : 0.92
1979	1.0 : 0.68	1.0 : 0.83	1.0 : 1.15	1.0 : 0.82
1980	1.0 : 0.66	1.0 : 0.90	1.0 : 1.15	1.0 : 0.88
1981	1.0 : 0.70	1.0 : 0.71	1.0 : 1.19	1.0 : 0.86
1982	1.0 : 0.62	1.0 : 0.66	1.0 : 1.09	1.0 : 0.79
1983	1.0 : 0.72	1.0 : 0.67	1.0 : 1.25	1.0 : 0.87
1984	1.0 : 0.60	1.0 : 0.71	1.0 : 1.22	1.0 : 0.82
1985	1.0 : 0.70	1.0 : 0.67	1.0 : 1.38	1.0 : 0.97
1986	1.0 : 0.64	1.0 : 0.73	1.0 : 1.26	1.0 : 0.87
1987	1.0 : 0.71	1.0 : 0.63	1.0 : 1.24	1.0 : 0.88

Recaptures not included

ratios close to 1:1 were also reported by other researchers working in waters close to shore (Herrick 1911; Templeman 1935a; Ennis 1971, 1974; Stewart 1972; Krouse 1973; Thomas 1973; Cooper et al. 1975; Briggs and Mushacke 1980).

Reproductive Characteristics

Female size at sexual maturity, development and fullness of egg masses carried by females and the percentage of berried females caught, were compared for preoperational and operational study periods. Female size at sexual maturity was determined by measuring the second abdominal segment and calculating the ratio of the abdominal width to the carapace length, and plotting that ratio against the carapace length (Templeman 1935b; Skud and Perkins 1969; Krouse 1973) (Fig. 4). Data for 1986 and 1987, represented as (*) in Figure 4, were compared to mean values collected from 1981 to 1985. Female size at sexual maturity was similar under 2- and 3-unit operating conditions. Females began to mature between 50 and 55 mm CL and all females were mature at sizes greater than 95 mm CL. The smallest berried females collected in our studies (62 mm CL) were between 54-56 mm CL when oviposition first occurred assuming 14% growth per molt and thus confirms the small size at which females mature in our area. Briggs and Mushacke (1979), working in western LIS, found that females began to mature at about 60 mm CL and most were mature at about 80 mm CL. In contrast to the LIS lobster population, females in northern waters (Maine) mature at a substantially larger size (80 mm CL, Krouse 1973). This was attributed to low water temperatures which retard reproductive maturation, whereas warmer summer water temperatures of LIS favor early maturation of females (Smith 1977; Aiken and Waddy 1980). The sexual maturity of males has been well documented and therefore was not investigated in our studies. Briggs and Mushacke (1979) reported that males in western LIS first reached maturity (i.e., produced mature spermatozoa), at 40 to 44 mm CL and over half were mature at 50 to 54 mm CL; in Maine, male lobsters also began maturing at relatively small sizes (50% mature at 44 mm CL, Krouse 1973).

Egg masses were examined from 1984 to 1987 to determine if the complement of eggs carried by females was normal. Smith (1977) expressed concern about the fecundity of berried females in western LIS when he found 10-14% of the berried females carried abnormally low numbers of eggs

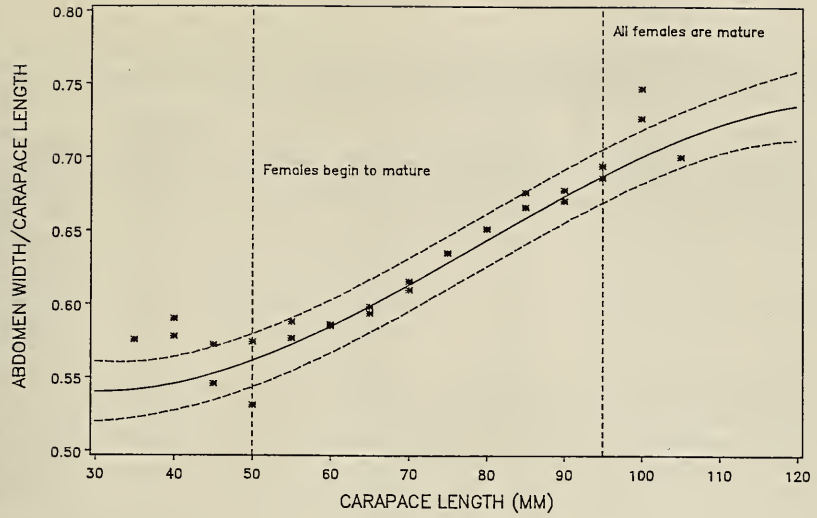

Fig. 4. Morphometric relationship between the ratio abdominal width/carapace length and the carapace length for data collected from 1981 to 1987 for female lobsters. (*) mean value for each 5 mm size for 3-unit data; (——) $y = a + bx + cx^2 + dx^3$ for 2-unit data; (- - -) upper and lower 95% C.I.

in 1976. Over 90% of the berried females in 1986 and 1987 had 1/2 or more the full complement of eggs (Table 7). This compares to 89% and 86% in 1984 and 1985. Only 3.6% in 1986 and 1.4% in 1987 of the berried females had less than 1/4 the normal complement of eggs. This compares to 3.7% in 1984 and 7.7% in 1985. From the above data it is apparent that the complement of eggs carried by berried females in our area is very good, and there has been no change following 3-unit operation.

The numbers of berried females caught during 1986 (134) and 1987 (158) were within the range of values reported since 1978 (58-171), as was the proportion caught at each station (Table 8). Twotree catches continued to yield a higher proportion of berried females (8.0-9.6%) than either Jordan Cove (3.0-3.2%) or Intake (2.3-1.9%). The mean size of berried females collected during 1986 was 78.0 mm, which was within the range of pre-operational values (77.0-81.2 mm). The 1987 mean size of 76.5 mm was the smallest value reported for berried females and was due to the fact that 90% of the berried females collected in 1987 were of sublegal size, whereas only 75% of the berried females caught in 1986 were sublegal. The proportion of sublegal-size berried females has, in general, been increasing since 1981 and may be related to the high exploitation rate of lobsters in LIS. The number of legal-size females that contribute to reproduction is limited by the high level of fishing pressure which removes most females shortly after reaching legal size. The fact that females become sexually mature and bear eggs at sizes well below the legal size is important because these individuals are able to spawn before growing to marketable size and thereby sustain

TABLE 7. The number of berried females examined for egg mass fullness and egg development from May through October 1984-1987.

Month	Number of Berried Females Examined	Number with $< \frac{1}{4}$ Complement	Number with $\frac{1}{4}$ Complement	Number with $\frac{1}{2}$ Complement	Number with $\frac{3}{4}$ Complement	Number with Full Complement	Developmental Stage
			1984				
MAY	28	0	1	4	11	12	Ripe eggs
JUN	16	4	1	2	1	8	Lt. Green with optical disks
JUL	4	0	0	1	1	2	"
AUG	18	0	0	0	4	14	New eggs
SEP	48	1	5	16	10	16	Black-dark green
OCT	50	1	5	7	16	21	"
TOTAL	164	6	12	30	43	73	
			1985				
MAY	34	3	4	8	3	16	Ripe eggs
JUN	19	6	1	0	5	7	Lt. Green with optical disks
JUL	7	2	0	0	4	1	"
AUG	17	0	1	1	3	12	New eggs
SEP	56	2	3	4	14	33	Black-Dark Green
OCT	89	4	6	8	23	48	"
TOTAL	222	17	15	21	52	117	
			1986				
MAY	21	0	1	7	5	8	Ripe eggs
JUN	6	1	0	2	0	3	Lt. Green with optical disks
JUL	0	0	0	0	0	0	
AUG	21	0	0	1	2	18	New eggs
SEP	49	1	1	4	10	33	Black-Dark Green
OCT	67	4	8	13	19	23	"
TOTAL	164	6	10	27	36	85	
			1987				
MAY	38	0	5	5	8	20	Ripe eggs
JUN	11	1	0	1	3	6	Lt. Green with optical disks
JUL	2	0	0	0	1	1	New eggs
AUG	14	0	0	0	3	11	Black-Dark Green
SEP	61	1	3	11	18	28	"
OCT	81	1	2	6	14	58	"
TOTAL	207	3	10	23	47	124	

TABLE 8. Carapace-length statistics and percentage of berried females caught at each station from 1978 to 1987.

	Jordan Cove	Intake	Twotree	N[a]	Length Range (mm)	Length Mean±95% CI	% Sublegal
1978	1.4	2.6	5.3	58	74 - 88	80.1 ± 1.04	67
1979	1.9	2.7	7.2	70	64 - 93	80.5 ± 1.28	54
1980	3.5	1.8	5.6	71	66 - 93	79.1 ± 1.27	64
1981	1.6	2.7	7.1	82	69 - 97	81.2 ± 1.35	52
1982	0.8	0.9	6.1	108	64 - 99	80.0 ± 1.08	58
1983	2.1	3.2	8.5	123	66 - 103	80.5 ± 1.04	60
1984	3.6	3.5	10.6	173	62 - 95	79.1 ± 0.87	67
1985	3.5	4.5	8.5	171	63 - 94	77.0 ± 0.81	82
1986	3.0	2.3	8.0	134	65 - 94	78.0 ± 0.95	75
1987	3.2	1.9	9.6	158	62 - 90	76.5 ± 0.67	90

[a] Recaptures not included

the population. In contrast, females in northern populations (Maine) begin to mature at sizes close to the legal size and only a small percentage of these females are able to spawn prior to reaching marketable size (Aiken and Waddy 1980).

Molting and Growth

The proportions of near-molting lobsters in the 1986 and 1987 total catches were 3.2% and 3.0% respectively, which were within the range of pre-operational values reported in NUSCO (1987a, range 2.5%-6.4%). The timing of peak molting was examined to determine the influence of water temperature during pre-operational and operational studies. The cumulative percentage of molting lobsters was compared for pre-operational and operational study years. The Gompertz growth function was then fitted to these data to estimate the time of peak molting as the time at which the inflection point of the growth curve occurred (Fig. 5). The inflection point of a Gompertz growth curve occurs at $t = \log(k/b)$, where (k) and (b) are parameters of the Gompertz function. During years when May temperatures were warmer than average, molting peaks occurred earlier, and conversely, they occurred later in the season when May temperatures were colder than average (Fig. 6). Templeman (1936) correlated the timing of molts with summer water temperatures in the Canadian Maritimes. He found that for each degree (C) of lower water temperature the first molting period was postponed for a week or more. The influence of varying water temperature on the molt cycle was also documented by Aiken and Waddy (1980) who found that lobsters exposed to 10°C, after a normal winter period, quickly entered pre-molt and progressed through to ecdysis. Secondary molts were not observed in the 1986-87 studies, although spring and fall molts were observed in some years when sampling was conducted from May to November and January to December (NUSCO 1987a).

Lobster growth was determined for lobsters that molted between the times of tagging and recapture. Carapace lengths at recapture (post-molt size) were related to carapace lengths at tagging (pre-molt size) using a simple linear regression which best describes growth per molt in crustaceans (Wilder 1953; Kurata 1962; Mauchline 1976).

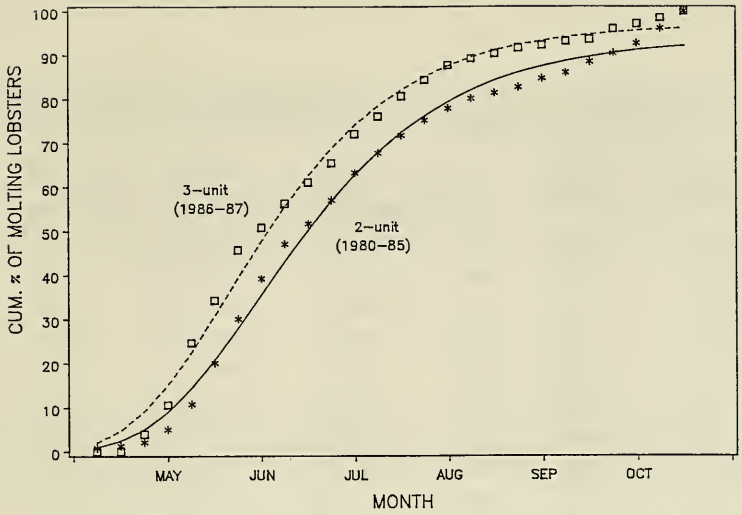

Fig. 5. Cumulative percentage of molting lobsters caught in pre-operational (* = 1980-85) and 3-unit studies (□ = 1986-87) and the Gompertz growth function that was fitted to the 2-unit (—) and 3-unit (- -) data.

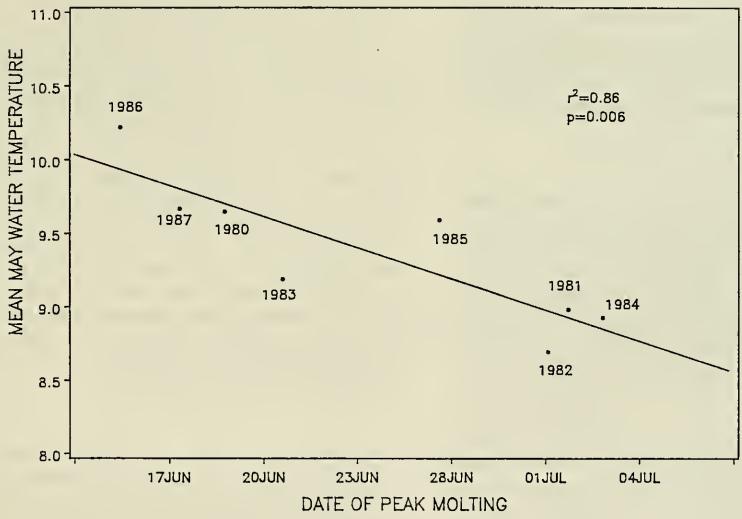

Fig. 6. Linear relationship between the date of peak molting (log b/k, from Gompertz growth function) and annual mean May bottom water temperature at all stations 1980-87.

Regression plots, equations and growth parameters for all lobsters (n = 987), males (n = 381) and females (n = 606) are presented in Figure 7. Growth per molt for all lobsters averaged 13.3% from 1986-87 and 13.9% from 1978-85. Female growth per molt averaged 13.9% during 3-unit operations and 13.7% prior to Unit 3 start up. Males had lower growth per molt during the 1986-87 studies (12.3%) compared to the pre-operational studies (14.1%). However, lower values for male growth (12.3%) had been reported in previous years (NUSCO 1980). In eastern LIS, Stewart (1972) reported 15.8% growth per molt for males, and 15.4% for females. Briggs and Mushacke (1984) reported 14.5% growth per molt for males and 12.5% for females in western LIS. Higher growth increments were reported by Cooper and Uzmann (1980) for an offshore lobster population, 18.7% for males and 16.7% for females. They attributed the lower growth of the inshore population to lobster inactivity during the colder months of the year.

Claw Loss

The percentages of lobsters caught missing one or both claws (culls) in 1986 (10.6%) and 1987 (10.3%) were lower than the average percentage culled in previous years (10.6%-15.5%) (Table 9). The proportion of culls at each station was similar in 1986 and 1987. The highest percentage of culls occurred at Intake, 14.7% in both 1986 and 1987, followed by Jordan Cove, 10.9%-11.9% and Twotree 6.8%-6.5%. The percentage of culls at Twotree has been lower than at the nearshore Jordan Cove and Intake stations since this study began (NUSCO 1987a). Working in eastern LIS, Smith (1977) reported 26.4% claw loss, whereas Briggs and Mushacke (1979) reported claw loss varying between 7.4 and 22.8% in western LIS. Since 1984, the percentage of culls in our catch was lower than in previous years due to the implementation of the escape vent regulation. This trap regulation requires that pots contain an opening to allow sublegal-sized lobsters to escape thereby reducing injuries and mortality associated with overcrowded pots (Landers and Blake 1985). Studies in Maine and Massachusetts by Pecci et

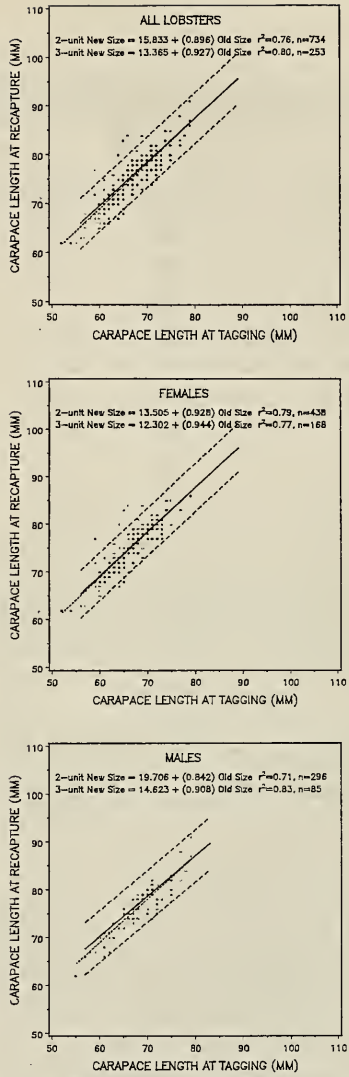
ALL LOBSTERS
2-unit New Size = 15.833 + (0.896) Old Size r²=0.76, n=734
3-unit New Size = 13.365 + (0.927) Old Size r²=0.80, n=253
FEMALES
2-unit New Size = 13.505 + (0.928) Old Size r²=0.79, n=438
3-unit New Size = 12.302 + (0.944) Old Size r²=0.77, n=168
MALES
2-unit New Size = 19.706 + (0.842) Old Size r²=0.71, n=296
3-unit New Size = 14.623 + (0.908) Old Size r²=0.83, n=85
CARAPACE LENGTH AT RECAPTURE (MM)
CARAPACE LENGTH AT TAGGING (MM)
50
60
70
80
90
100
110

Fig. 7. Linear regressions for carapace lengths at tagging and recapture times for all lobsters, males and females for data collected during pre-operational studies 1978-85 (——) $y = a + bx$; (- - -) upper and lower 95% C.I.; data for 3-unit studies (1986-87) represented as individual points (*).

TABLE 9. Claw loss for lobsters caught in wire pots from 1978 to 1987.

Year	Percent Cull	Percent Missing One Claw	Percent Missing Two Claws
1978	14.9	14.0	0.9
1979	15.5	14.4	1.2
1980	13.6	12.2	1.5
1981	12.0	11.1	1.0
1982	11.1	10.4	0.7
1983	12.4	11.6	0.8
1984	10.6	9.8	0.7
1985	11.1	10.4	0.7
1986	10.6	9.8	0.8
1987	10.3	9.5	0.7

al. (1978) reported that trap-related injuries resulting in claw loss were often associated with water temperature, fishing pressure (i.e., handling by lobstermen), trap soaktime, and physical condition of the lobster (i.e., its nearness to molting).

Tagging Program

The numbers of lobster tagged in 1986 and 1987 were 5,698 and 5,680 respectively. These values were within the range of values established in pre-operational studies (Table 10). Recapture percentages during the same period were 21.0% and 23.9%, and also within the range of pre-operational percentages (15.9-23.9%). The percentage of commercial recaptures was 20.2% in 1986 and 17.8% in 1987. These values were lower than in previous years (range 21.1-47.6%) due to the implementation of a new trap regulation in 1984 which required escape vents in commercial traps. Lobstermen recaptured 27.7 to 47.6% of our tagged lobsters from 1978 through 1983, an overall average of 37.4%. When the escape vent went into effect in 1984, lobstermen recaptured fewer of our tagged lobsters (21.5-17.8%), an overall average of 18.8%. In contrast, our traps do not have escape vents and subsequently our rates of recapture increased from 17.0% to 22.7% after the regulation went into effect. Landers and Blake (1985) demonstrated the retention rate of tagged lobsters in vented and unvented traps. With the regulation in force, the mean size of tagged lobsters caught in commercial traps fitted with escape vents was larger than the mean size caught in unvented traps (i.e., a number of the tagged sublegal-sized lobsters were escaping from pots which had escape vents).

Movement

Movement patterns of the local lobster population were assessed using recapture data from our sampling efforts and those of commercial lobstermen. Because lobsters were tagged and released at the station where captured, any movement between stations could be detected at recapture. During 1986 and 1987, 97% of the lobsters were recaptured at the release station compared to 95% in pre-operational study years indicating that movement between stations continues to be minimal. Of the exchanges that did occur, most were between the nearshore Jordan Cove and Intake stations. Tagging studies conducted in eastern LIS by Stewart (1972) demonstrated the homing behavior of nearshore lobster populations.

TABLE 10. Summary of tag and recapture studies from 1978 through 1987.

			NUSCo			Commercial		
Year	No. tagged	Mean CL (mm)	Returns No.	%	Mean CL (mm)	Returns No.	%	Mean CL (mm)
1978	3193	73.6	508	15.9	75.5	884	27.7	81.1
1979	3732	72.8	722	19.4	75.1	1776	47.6	77.5
1980	3634	75.5	522	14.4	75.7	1363	37.5	76.4
1981	4246	72.4	707	16.7	74.8	1484	35.0	76.3
1982	7575	70.9	1278	16.9	73.2	2518	33.2	75.5
1983	5160	71.8	936	18.1	73.6	2266	43.9	76.9
1984	5992	71.9	1431	23.9	73.0	1289	21.5	78.7
1985	5609	71.3	1235	22.0	73.1	1185	21.1	78.3
1986	5698	70.2	1194	21.0	72.3	1153	20.2	78.3
1987	5680	70.4	1356	23.9	72.8	1010	17.8	78.6

Tag returns from commercial lobstermen fishing within 8 km around MNPS accounted for 94% and 97% of all commercial returns during 1986 and 1987, respectively, which was similar to returns during pre-operational studies (93%). Of the 103 lobsters that were recaptured outside the study area (> 8 km) during 1986 and 1987, 98% moved to the east. Several of these lobsters traveled a great distance; 2 were recaptured off Point Judith, and 1 off Watch Hill, RI, 1 tag was returned from Buzzards Bay, and 1 from Nantucket Shoals, MA. Based on tag returns from the deep water canyons on the edge of the continental shelf (Hudson Canyon, n = 2; Veatch Canyon n = 1), some of our lobsters moved offshore during the 1986-87 studies. Similar offshore movement patterns were established in pre-operational studies (NUSCO 1987a). Results from other tagging studies in LIS indicated a similar easterly trend in lobster movement (Lund and Rathbun 1973). Other researchers working in waters off New England and on the continental shelf demonstrated similar exchanges between the inshore and offshore populations (Saila and Flowers 1968; Uzmann et al. 1977; Fogarty et al. 1980). Based on our sampling efforts and commercial returns around MNPS, lobster movements in our study area were typical of nearshore populations and agreed with other tagging studies conducted in coastal waters of eastern North America which indicated localized lobster movement (Templeman 1940; Wilder and Murray 1958; Wilder 1963; Cooper 1970; Stewart 1972; Cooper et al. 1975; Fogarty et al. 1980; Krouse 1980, 1981; Campbell 1982; Ennis 1984; Campbell and Stasko 1985).

Entrainment

Lobster larvae were collected from mid-May to early-July during 1986 and 1987. Stage I lobster larvae predominated in samples collected in 1984, 1985, and 1987, and stage IV in 1986 (Table 11). Seventy-seven percent of these larvae (Stage IV) were collected in 4 night samples during the last week of June 1986. More larvae were collected in night than in day samples from 1984-1986. However, during 1987 more larvae were caught in day samples, when a single sample contained 52 Stage I larvae, representing 50% of all Stage I larvae collected in 1987. Variability in both numbers and stages of larvae collected in our

TABLE 11. Summary of lobster larvae entrainment data from 1984 to 1987.

	Stage I	Stage II	Stage III	Stage IV	Total
			1984		
Day	15	0	0	1	16
Night	73	1	1	11	86
Total	88	1	1	12	102
			1985		
Day	56	0	3	2	61
Night	69	1	2	10	82
Total	125	1	5	12	143
			1986		
Day	33	1	4	8	46
Night	54	10	11	111	186
Total	87	11	15	119	232
			1987		
Day	104	4	5	3	116
Night	56	6	3	4	69
Total	160	10	8	7	185

samples was high, similar to findings by other researchers working with lobster larvae (Bibb et al. 1983; Lux et al. 1983; Blake 1984). The contagious distribution of lobster larvae has been associated with surface water circulation patterns (Fogarty 1983), which generate sea surface "fronts". These fronts, visible on the surface waters as "scum", "foam", or "slick" lines, occur in the vicinity of MNPS, and were reported to contain high densities of planktonic organisms, including lobster larvae (Cobb et al. 1983; M. Blake personal communication).

Night samples contained more larvae than day samples in 3 of the 4 study years. This may be due to the design of the intake structures, which have curtain walls extending about 2 m below MLW. This means that cooling water is drawn from 2 m below the surface. Since the early stages of lobster larvae are photopositive and disperse from surface waters during darkness (Templeman 1939), they are more susceptible to entrainment at night regardless of tidal stage. However, during daylight hours lobster larvae predominate in surface samples (Fogarty 1983; Fogarty and Lawton 1983). Therefore larvae avoid entrainment during the day due to their photo-behavior and the intake structure design.

The density of lobster larvae in the MNPS cooling waters was estimated as the δ-mean (see Delta Distribution Section of this report and also Pennington 1983). The annual δ-mean density (number per 1000 m^3) of lobster larvae collected in entrainment samples was higher in 1986 (0.88) and 1987 (0.63) than 1984-85 densities (0.42-0.43, Table 12). The estimated number of lobster larvae entrained through the MNPS cooling water systems in 1986 and 1987, was 548,635 and 304,694, respectively. The higher estimates in 1986-87, relative to 1984 and 1985 values of 79,511 and 138,820, respectively, were related to the fact that Unit 3 began operating in 1986. Entrainment estimates were based on both the

TABLE 12. Annual mean densities (number per 1000 m^3) of lobster larvae in entrainment samples during their season of occurrence and annual entrainment estimates with 95% C.I. for MNPS from 1984 through 1987.

Year	Dates Found	Mean Density[a] (n per 1000 m^3)	95% CI	Estimate	95% CI
1984	21May-10Jul	0.42	0.19-0.65	79,511	35,983-123,100
1985	15May-29Jul	0.43	0.22-0.64	138,820	71,024-206,615
1986[b]	14May-14Jul	0.88	0.43-1.33	586,226	286,451-886,000
1987	18May-7Jul	0.63	0.29-0.97	304,695	140,256-469,134

[a] Mean densities are calculated as the δ-mean (see Delta Distribution Section and Pennington 1983).

[b] Unit 3 began commercial operation

density of larvae in the cooling waters and total cooling water volumes; since Unit 3 requires almost double the cooling water demand of Units 1 and 2 combined, a doubling of the estimated number of lobster larvae entrained was expected when all units were operating during the larval season. Projecting the impact associated with lobster larvae entrainment to the population level (adult lobsters) was difficult due to the lack of knowledge regarding larval and post-larval stages of lobsters (Phillips and Sastry 1980). Given that lobsters require several years of growth to reach a trappable size, our studies of adults would not detect 3-unit entrainment effects until 5-6 years after an impact occurred.

During 1986, 6.5% and in 1987, 3.8% of the lobster larvae survived after passing through the plant's cooling water system suggesting that entrainment mortality may be lower than the assumed 100%. Similar findings at other power stations have been reported. Collings et al. (1981) reported 14% survival for lobster larvae (Stage II) collected at the Canal Electric Company, Sandwich, MA.

Impingement

Impingement of lobsters on the Unit 1 and 2 intake screens has been summarized for the period 1975 to 1985 in NUSCO (1987a). Throughout these studies several measures were investigated to mitigate impingement losses, including the use of underwater barriers, acoustic and light deterrents and more recently fish return systems (sluiceways). In 1983, a sluiceway system was installed in the Unit 1 intake structure which returned 100% of the lobsters caught on the screens back to Niantic Bay. A sluiceway was also constructed at Unit 3 and operated during 1986 and 1987 (NUSCO 1987b).

The estimated number of lobsters impinged at Unit 2, which does not have a sluiceway, was 676 and 825 in 1986 and 1987, respectively (Table 13). These values were within the range of values reported for impingement at Unit 2 (261-1220). The impingement of lobsters was highest during the summer months and coincided with peak catch in traps (NUSCO 1987a).

The mean sizes of lobsters impinged during 1986-87 were 55.7 and 55.8 mm CL, respectively, which were within the range of pre-operational values 48.6 to 64.9 mm CL and continued to be

TABLE 13. Annual impingement estimates for lobster collected at Units 1 and 2 from 1978 to 1987.

	Unit 1	Unit 2	Both Units
1978	245	261	506
1979	323	426	749
1980	368	405	773
1981	665	1009	1674
1982	938	1041	1979
1983	999	497	1496
1984	a	1220	1220
1985	a	480	480
1986	a	676	676
1987	a	825	825
Total	3538	6840	10378

[a] Unit 1 sluiceway began operating December 1983.

smaller than the trap catch values (NUSCO 1987a). Smaller lobsters enter the intake through the course bar racks (bar spacing 6.4 cm) more readily than larger lobsters which are seldom impinged. Male to female sex ratios of impinged lobsters during 1986 and 1987 were 1.0:0.46 and 1.0:0.38, respectively. These values were slightly lower than the range of pre-operational sex ratios reported from 1982 to 1985 (1.0:0.47 to 1.0:0.58) and reflected the higher abundance of male lobsters nearshore at the Jordan Cove and Intake stations (1.0:0.6 -1.0:0.7, NUSCO 1987a). The percentage of impinged lobsters missing one or both claws (culls) during 1986-87 (27%) was lower than pre-operational values (30-50%). Impinged lobsters suffered greater claw loss when compared to trap catch values (wire pots, 10-16%) due to the high pressure (80 psi) wash used to remove debris from the traveling screens (NUSCO 1987a).

Survival of lobsters impinged at Unit 2 during 1986 (97%) was higher than the ten year range of survival values reported from 1975-85 (64-80%). During 1987 survival was slightly lower (62%), due to higher impingement of lobsters during the summer; more than half of all lobsters were impinged from May through September in 1987. Historically, mortality of impinged lobsters was highest during the peak molting period (May-June) when lobsters were soft and easily injured, and during the later summer months when water temperatures were highest (August-September; NUSCO 1987a).

Summary

1. Total CPUE during 1986 and 1987 was 1.70 and 1.72, respectively, within the range of values reported during 2-unit operations (0.85-2.10). Legal CPUE was lower during 1986 and 1987 (0.097, 0.089) when compared to previous years' results and may be related to increased fishing pressure. A 50% decline in catch at Jordan Cove occurred from August to September 1986 and was related to 3-unit operations. Sediments in the discharge area were scoured and subsequently deposited in Jordan Cove, where lobster habitats were buried by sediments. This decline in catch was only temporary, since catches in October 1986 and throughout 1987 at Jordan Cove were normal and indicated that sediments

had stabilized and lobsters had returned to the affected area.

2. The mean size of lobsters caught during 1986 (70.1 mm) and 1987 (70.2 mm) was smaller than values reported in previous years (range 70.7-71.8 mm) due to the lower CPUE of legal-sized lobsters during 1986-87.

3. Male to female sex ratios during 1986 and 1987 were 1.0:0.87 and 1.0:0.88, respectively, within the range of values in previous years. The Twotree station continued to yield a higher proportion of females than the other two nearshore stations, a trend consistent since the study began.

4. Female size at sexual maturity was similar during 2- and 3-unit operations; females began to mature between 50 and 55 mm CL and all females were mature at sizes greater than 95 mm CL. The mean CL of berried females during 1986 (78.0 mm) and 1987 (76.5 mm) and the proportions of sublegal size berried females caught in 1986 (75%) and 1987 (90%) confirmed the small size at first sexual maturity of females in the Millstone area.

5. Lobsters that were near molting comprised 3.2% and 3.0% of the 1986 and 1987 total catches, respectively, which were within the range of values reported during 2-unit operations. Growth per molt averaged 13.3% in 1986-87 compared to 13.9% from 1978-85.

6. The percentage of culls in 1986 (10.6%) and 1987 (10.3%) was lower than the average percentage culled in previous years (range 10.6%-15.5%) and due to the implementation of the escape vent regulation in 1984.

7. The number of lobsters tagged in 1986 (5,698) and 1987 (5,680) was within the range of annual values for lobsters tagged in pre-operational studies. Recapture rates for 1986 (21.0%) and 1987 (23.9%) were also similar to pre-operational values (range 15.9%-23.9%). Lobstermen recaptured 20.2% of our tagged lobsters in 1986 and 17.8% in 1987.

8. Lobster movements were localized, since 94% and 97% of all commercial recaptures were made within 8 km of Millstone Point during 1986 and 1987, respectively. Several lobsters moved outside LIS and were caught in waters off R.I. and MA.; 3 lobsters moved offshore during 1986-87, where they were caught in deep water canyons on the edge of the continental shelf.

9. Lobster larvae densities (number per 1000 m^3) in entrainment samples were higher in 1986 (0.88) and 1987 (0.63) when compared to 1984-85 (0.42-0.43). The estimate of total lobster larvae entrainment, based on sample density and total MNPS cooling water demand, was also higher in 1986 (548,635) and 1987 (304,694) when compared to 1984-85 (79,511-138,820). Lobster larvae survival was 6.5% and 3.8% in 1986 and 1987, respectively. More stage IV larvae were collected in 1986 compared to 1984, 1985, and 1987 when greater numbers of stage I larvae were collected.

10. The estimated numbers of lobster impinged at Unit 2 during 1986 and 1987 were 676 and 825, respectively, these values were within the range of values reported in previous years (261-1220). Fish return systems at Units 1 and 3 improved overall survival of impinged lobsters. Based on impingement of all organisms at Unit 2 since 1972, a request made by NUSCO to discontinue impingement monitoring at Unit 2 was accepted by the CT DEP in December 1987.

Conclusion

Our studies indicate that the local lobster population is heavily exploited; more than 90% of legal sized lobsters are removed by fishing. The commercial and recreational catches are highly dependent on the number of lobsters in the

prerecruit size class. Legal CPUE values over all stations during 1986-87 were the lowest reported since this study began, although legal CPUE has declined since 1978 and may be related to the high fishing pressure in LIS. During simultaneous 3-unit operation, a short term impact on lobsters occurred at Jordan Cove in August 1986 due to scouring of fine silt in the discharge area. Silt originating from the discharge area fouled lobster habitat in Jordan Cove and temporarily displaced lobsters. Once sediments stabilized, lobsters reinhabited the area, and catch rates at Jordan Cove in October 1986 and throughout 1987 were normal and typical of previous study results. A similar short term impact occurred following dredging activities in the vicinity of the intakes during 1985; dredging removed lobster habitat (shelters) and thereby displaced lobsters from the area. Lobsters returned to that site soon after the sediments stabilized and CPUE values for 1986-87 were comparable to the other stations.

Because lobsters require at least 4-5 years of growth before they are vulnerable to our traps, and an additional 2 years to reach marketable size, there is a lag of about 6-7 years between the time of a potential impact on larvae and the time at which we can detect that impact. The sensitivity of our program in defining population trends (i.e., observing the strong prerecruit class in 1982) and impacts (displacement of lobsters as a result of scour and dredging) is vital to the evaluation of impacts associated with the operation of three units at Millstone Point. If changes occur in the local lobster population, they will be detected by the alteration of the basic population parameters now being monitored. Changes in these parameters during 3-unit operations will demonstrate the effects (if any) of MNPS operations on the local lobster population.

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Winter Flounder Studies

Introduction

This section summarizes recent research on the winter flounder (*Pseudopleuronectes americanus*) and builds upon the data base previously assembled by Northeast Utilities (NU) as part of environmental studies for the Millstone Nuclear Power Station (MNPS). Due to the local abundance and importance of the winter flounder to the Connecticut sport and commercial fisheries, this species has been intensively studied since 1973 and considerable data have been collected on its life history and population dynamics. A summarization of the data, results, and conclusions for all aspects of the work from 1973 through early 1986 was included in NUSCO (1987). This time frame represented the pre-operational period for MNPS Unit 3, which began commercial operation in late April of 1986.

The population of winter flounder is composed of reproductively isolated stocks which spawn in specific estuaries and coastal areas from Nova Scotia to New Jersey (Lobell 1939; Perlmutter 1947; Saila 1961; Leim and Scott 1966). Most adults enter natal estuaries in fall and early winter and spawning occurs in late winter and early spring. Females usually mature at age 3 and 4 and males at age 2 and average fecundity is about 500,000 eggs per female. Eggs are demersal and hatch in about 15 days, depending upon water temperature. The larval stage lasts about 2 months, also depending upon water temperature. Small larvae are planktonic and remain in natal estuaries to a great extent, although some may be carried out into open waters by tidal currents. Some of these larvae may return to the estuary on subsequent incoming tides, but the rest are lost from the system. Larger larvae maintain some control over their position by vertical movements and also may spend considerable time on the bottom. Following metamorphosis, most demersal juveniles remain in the estuary in shallow waters. Immature yearling (age 1) winter flounder become photonegative and though many remain within the estuary, are usually found in deeper water than age 0 young-of-the-year (Pearcy 1962; McCracken 1963). Many adults stay in estuaries following spawning, while others disperse into deeper waters. By summer, most have left shallow waters as their preferred temperature range is 12-15°C (McCracken 1963). However, some remain inshore and may escape temperatures above 22.5°C by burying themselves in cooler bottom sediments (Olla et al. 1969). Adults are omnivores and as opportunistic feeders eat a wide variety of algae and benthic invertebrates. They are sight feeders and are usually active only during the day. Additional details regarding winter flounder life history, physiology, behavior, and population dynamics may be found in Klein-MacPhee (1978).

Because winter flounder stocks are localized, our studies have focused on the population spawning in the Niantic River to determine if MNPS impacts of impingement and entrainment have caused or would cause changes in local abundance beyond those expected from natural variation. Operation of Unit 3 approximately doubled the volume of cooling water used by MNPS and some impacts could be expected to increase commensurately. In assessing the impact of winter flounder larval entrainment, our efforts have been aimed at estimating the number of individuals annually entrained and measuring changes at the adult population level. The approach chosen to carry out these two basic tasks consisted of a combination of sampling programs and analytical methods designed to provide a preliminary short-term assessment capability and, ultimately, a long-term assessment tool in the form of a comprehensive simulation model, which includes hydrodynamics and population dynamics submodels. Short-term empirical assessment methods (Horst 1975; Goodyear 1978) and a preliminary

deterministic population model (Hess et al. 1975; Saila 1976) were used when, only 3 to 4 years into the winter flounder research program, complete data specific to the local winter flounder population were not yet available (NUSCO 1983). In recent years, the work has increasingly been directed towards more specific and detailed studies of early life history and on the critical stock-recruitment relationship. This has been reflected by studies designed to address specific concerns of NU and the Connecticut Department of Environmental Protection (CT DEP) (NUSCO 1988a, 1988b). The information will be incorporated into the models currently under development, which should be available for use within about a year. This report discusses the results of ongoing winter flounder research and provides brief descriptions of the models that will be used for impact assessment.

Materials and Methods

Adult and juvenile studies

Abundance estimation of the Niantic River spawning population of adult winter flounder has been based on mark and recapture methodologies and details concerning annual surveys from 1976 through 1986 are summarized in NUSCO (1987). Since 1982, each survey started after ice-out in the river in mid to late February and ended in early April, when the proportion of reproductively active females decreased to less than 10% of all females examined for two consecutive weeks. The Niantic River was subdivided into a number of areas (stations) for each survey (Fig. 1); no samples were taken outside of the navigational channel in the lower portion of the river since 1979 because of an agreement with the East Lyme-Waterford Shellfish Commission to protect bay scallop (*Argopecten irradians*) habitat. Collections were made during 2 or 3 days each week and were usually allocated to a station according to the expected abundance of winter flounder with more tows taken in areas where fish were most numerous.

Winter flounder were captured with a 9.1-m otter trawl (6.4-mm bar mesh codend liner), which has usually been towed at a standardized distance of 0.55 km since 1983; tows of variable length were taken previously. The standard distance was chosen because it represented the maximum tow length at station 1 and because using the same tow length at all stations was expected to reduce variability in calculating catch-per-unit-effort (CPUE), used as an index of abundance. In 1987, tows one-half or two-thirds of this length were frequently taken in the upper river (mostly at station 51) to avoid overloading the trawl with algae and detritus. Tow time and numbers of fish from tows of shorter distances in 1987 were compared to those from tows of the standard distance (0.55 km) to determine if the catches were proportional to distance of tow for computation of CPUE. Because catch data from station 2 were also used for the trawl monitoring program, hauls at that station were maintained at the standard distance of 0.69 km for that sampling program.

Mostly because of differences in tidal currents, wind, and amounts of extraneous material collected in the trawl, tow times for the standardized distances varied and were usually greater in the lower than in the upper river. For 1983-87, the mean duration for standardized tows at stations 1 and 2 was 15.7 min and at stations 4, 51, 52, 53, and 54 was 12.5 min. Tows from 1976-82, when tow distance varied, that had shorter or longer duration compared to the distribution of tow times from 1983-87, when tow distance was uniform, were excluded from data analyses and calculation of CPUE. For comparisons among years, all catches of winter flounder larger than 15 cm made during a 4-week period from mid-March through early April were standardized to either 15-min tows (stations 1 and 2) or 12-min tows (all other stations) and annual median CPUE values were determined. A 95% confidence interval was calculated for each median using a distribution-free method, where the order statistics for the upper and lower confidence limits were plus or minus the square root of the sample size from the order statistic describing the median

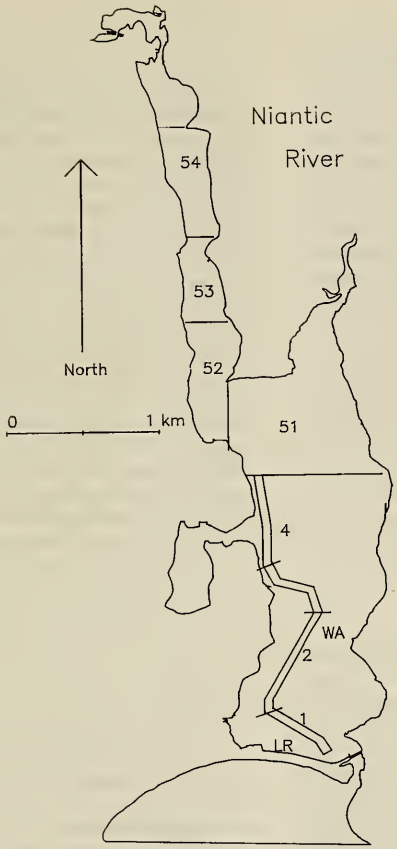


Fig. 1. Location of Niantic River adult and juvenile winter flounder sampling stations used from 1983 through 1987

(Snedecor and Cochran 1967). The CPUE of juveniles smaller than 15 cm taken in the Niantic River during the spawning season was determined in a manner similar to that for adults. The catch of fish from stations 1 and 2 (Fig. 1) was used, as in most years juveniles were scarce in the upper river.

The winter flounder caught in each tow during the adult abundance survey were placed immediately into water-filled containers aboard the survey vessel. At least 200 randomly selected fish were measured to the nearest 0.1 cm in total length during each week of the population abundance survey in all years. Since 1983, all winter flounder

larger than 20 cm have been measured and sexed. Non-measured fish were classified into various length and sex groupings, depending upon the year; at minimum, all fish caught can be classified as smaller or larger than 15 cm. Since 1977, the sex and reproductive condition of the larger winter flounder were determined either by observing eggs or milt or by the presence (males) or absence (females) of ctenii on the caudal peduncle scales of the left side (Smigielski 1975). Following measurement or classification, all fish 15 (1977-82) or 20 (1983-87) cm or larger were marked with a number or letter made by a brass brand cooled in liquid nitrogen; the mark was changed weekly. Fish recaptured were noted and remarked with the brand designating the week of their recapture. In 1976, fish were fin-clipped and recaptures were marked with a numbered spaghetti tag. The log-likelihood ratio test (G-test of Sokal and Rohlf 1969) was used to compare the proportions of winter flounder marked and recaptured in each category of sex, length interval, and station. The probability level chosen to reject the null hypothesis in this and other statistical tests given in this section was $p \leq 0.05$.

Estimates of abundance of all winter flounder 15 or 20 cm and larger in the Niantic River during the spawning season were obtained from the mark and recapture data using the Jolly (1965) model. The actual computations were done using a computer program (Davies 1971) of Jolly's model. As a result of a comprehensive review of our mark-recapture methodology, a composite index of relative abundance was developed to describe the number of adult winter flounder spawning in the Niantic River each year (NUSCO 1986a, 1987). This index was computed by averaging the central weekly estimates of N (scaled as thousands) from the Jolly model, with the first and last estimates excluded when sufficient data were available. These Jolly estimates are less reliable and were eliminated from the computations in all years except when the number of values used would have been less than three. The standard error of N (σ) was determined as:

$$\hat{\sigma}_N = (\tfrac{1}{3})\sqrt{\text{Var of}(N_1) + \text{Var of}(N_2) + \text{Var of}(N_3) \ \ldots} \qquad (1)$$

where N is the weekly Jolly estimate of population size

Using observations of reproductive condition from 1981-87, probit analysis (SAS Institute Inc. 1985) was used to estimate the length at which 50% of all females were mature. An index of the number of females reproducing in the Niantic River each year since 1977 was created by estimating their abundance in each 1-cm length increment starting with 26 cm. Fecundity (annual egg production per female) was estimated from length-frequencies and a length-fecundity relationship determined for Niantic River winter flounder (NUSCO 1987). Annual average fecundity was determined from the sum of all individual egg production estimates divided by the number of spawning females for each year. A relative index of annual egg production (in billions) was found by summing all individual estimates.

The catch of winter flounder taken in the trawl monitoring program from 1976 through 1987 (see Fish Ecology section for methods) was also used as an index of abundance. CPUE was expressed as the annual δ-mean (Pennington 1986; see the Delta Distribution section of this report for details concerning this abundance index) during a calendar year to facilitate comparisons with other regional abundance indices. For other analyses, length-frequency information was used to partition the catch into size groups smaller and larger than 15 cm.

Both the annual median CPUE of adult winter flounder taken in the Niantic River during the spawning season (1976-87) and the trawl monitoring program annual δ-mean (1976-86) were

compared to other indices of winter flounder abundance to determine if similar trends were apparent. These included National Marine Fisheries Service (NMFS) statistics for Rhode Island and a University of Rhode Island (URI) long-term (1966-86) trawl survey in Narragansett Bay (M. Gibson, Rhode Island Department of Environmental Management, pers. comm.), and Connecticut-licensed trawler catches from 1979 through 1987 (E. Smith, CT DEP, pers. comm.). The NMFS statistics were CPUE expressed as the number of pounds of winter flounder per 50-ton unit for Rhode Island vessels (1947-87) and as the number of pounds per directed trip in Statistical Area 539 (Narragansett Bay and Block and Rhode Island Sounds), available from 1964 through 1987. The Connecticut commercial CPUE was calculated as the number of pounds per hour of trawling. The URI data are annual δ-means determined from monthly sums of winter flounder taken during weekly sampling by trawl. Due to an apparent preponderance of juveniles in the latter time-series (Gibson 1987), the annual CPUE values were lagged 1 year before making comparisons. Additional information concerning the URI time-series may be found in Jeffries and Terceiro (1985) and Jeffries et al. (1986). Abundance indices were correlated using the nonparametric Spearman rank-order correlation. Historical records of winter flounder catches given by Perlmutter (1947) and NMFS (1987) were also examined.

The annual abundance data for the Niantic River spawning stock from 1976 through 1987 were used to develop a stock and recruitment model. All fish 21.4 cm and larger were considered to be adults (age 3 and older). Annual median CPUE values of winter flounder 15 cm and larger were adjusted to account for fish larger than this minimum length to estimate relative parental stock size for each year. Similarly, the CPUE were partitioned to determine a value for age 3 (21.4-28.0 cm) fish each year. The latter value was multiplied by 1.938 in order to account for life-time reproductive contribution and to scale the values into similar units for comparison with parental stock size estimates. This scaling factor was determined from estimates of maturity and mortality (NUSCO 1987) and an assumed maximum life span of 12 years for Niantic River winter flounder. The adjusted CPUE values of the age 3 recruits were plotted against the parental stock size CPUE for 3 years prior. As a dome-shaped recruitment curve with reduced recruitment at high parental stock sizes was suggested by this procedure, a Ricker (1954, 1975) stock and recruitment model was fit to these data using nonlinear regression methods (SAS Institute Inc. 1985) where:

$$R = \alpha P \exp(-\beta P) \qquad (2)$$

where R = CPUE index of the number of age 3 recruits

P = CPUE index of parental stock size

α = dimensionless parameter associated with density-independent mortality

β = parameter describing the instantaneous rate of density-dependent mortality with dimension of 1/P

Water temperature, believed to be an important environmental variable in the early life history of winter flounder, was considered as an additional parameter in order to improve the fit of the observed data to the model. Continuous water temperature records were available from the intakes of MNPS Units 1 and 2 and mean water temperatures during 1976 through 1987 were found for individual and for various combinations of months encompassing the January through May spawning and larval recruitment period. Means over an 11-year (1976-86) period were also determined for the same months and groups. For each time period, deviations from the long-term mean were computed and compared (Spearman rank-correlation) with annual estimated age 3 recruitment. Water temperature, expressed as a positive or negative deviation from the long-term mean, having the highest correlation with recruitment was used as a third parameter in the Ricker model:

$$R = \alpha P \exp(-\beta P) \exp(-\varphi T) \qquad (3)$$

where T = annual temperature deviation from a long-term mean

φ = dimensionless parameter that relates log-recruitment to annual water temperature deviations

Larval studies

The history and development of the current ichthyoplankton sampling programs were given in NUSCO (1987). Samples for winter flounder larvae in 1986 and 1987 were taken in Niantic River at stations A, B, and C and in Niantic Bay at EN (entrainment sampling) and NB (Fig. 2).

Fig. 2. Location of stations sampled for larval winter flounder

Collections in the river and at NB were made with a 60-cm bongo sampler with 3.3-m long nets towed at approximately 2 knots and weighted with a 28.2-kg oceanographic depressor. Volume of water filtered was determined using a single General Oceanics (GO) flowmeter (model 2030) mounted in the center of each bongo opening. A stepwise oblique tow pattern was used with equal sampling time at surface, mid-depth, and near bottom. The length of tow line necessary to sample the mid-water and bottom strata was based on water depth and the tow line angle as measured with an inclinometer. Winter flounder larvae entrained by MNPS were collected at Units 1 and 2 discharge (station EN) using a gantry system to deploy a 1.0 x 3.6-m plankton net. Four GO flowmeters were positioned in the mouth of the net to account for horizontal and vertical flow variation; sample volume was deter-

mined by averaging the four volume estimates from the flowmeters.

All sampling at EN was conducted with 333-μm mesh nets. On the bongo sampler, 202-μm mesh nets were used from February through the first week of April and 333-μm mesh nets were used during the remainder of the season. The bongo sampler was towed for 6 min at station A, B, and C (filtering about 120 m^3) and for 15 min at station NB (filtering about 300 m^3). Generally, the net was deployed at EN for 5 to 6 min (filtering about 400 m^3), but this varied depending upon plant operations (number of circulating pumps). All ichthyoplankton samples were preserved with 10% formalin. At the three river stations, jellyfish medusae were sieved (1-cm mesh) from the sample and measured volumetrically (ml).

During the occurrence of larval winter flounder in 1986 and 1987, sampling time and frequency varied with station, season and year. At EN, collections were taken during the day and night (two replicates during each) once a week in February and June and similarly during 4 days each week from March through May. Single bongo tows were made at NB biweekly (day and night) in February and March, and weekly in April through the end of the larval winter flounder season, except that weekly day and night samples were collected in March 1987. Preliminary tows were made during the daytime in February in the upper portion of the Niantic River (ice permitting) to determine when larval winter flounder were present. From the first larval occurrence through the first week of April, single daytime tows at each station were made twice weekly within an hour of low slack tide. During the last 3 weeks of April, single day and nighttime bongo tows were made twice weekly. The day samples were collected within an hour of low slack tide and the night samples during the second half of a flood tide. During the remainder of the season until the disappearance of larvae at each station, tows were made twice a week only at night during the second half of a flood tide. This varying sampling scheme, based on information from previous sampling, was designed to increase efficiency in data gathering and reduce sampling biases (NUSCO 1987).

Only one of the replicates from a bongo tow or entrainment collection was processed in the laboratory. Samples were split to at least one-half volume and larvae were identified and counted using a dissecting microscope. Up to 50 randomly selected winter flounder larvae were measured to the nearest 0.1 mm in standard length (snout tip to notochord tip). The developmental stage of each measured larva was recorded using the following identification criteria:

Stage 1.	The yolk-sac was present or the eyes were not pigmented (yolk-sac larvae)
Stage 2.	The eyes were pigmented, no yolk-sac was present, and no fin ray development
Stage 3.	Fin rays were present, but the left eye had not migrated to the mid-line
Stage 4.	The left eye had reached the mid-line, but juvenile characteristics were not present
Stage 5.	Transformation to juvenile was complete and intense pigmentation was present near the caudal fin base

Larval data analyses were based on standardized densities per 500 m^3 of water sampled. An average of weekly densities was used in analyses because weekly sampling frequencies varied due to sampling design and weather conditions. The geometric mean was chosen because these data generally followed a lognormal distribution (see the Delta Distribution section of this report). Previously, weekly means were determined arithmetically and the results reported in NUSCO (1987) may differ from those herein. For comparisons of river and bay data and also for some

previous years, daytime samples after April were excluded, except for estimating larval entrainment with station EN data. During this period, daytime samples were not collected in the river because these samples underestimated abundance due to the fact that older larvae apparently remained near the bottom during the day and were not susceptible to the bongo sampler (NUSCO 1987).

Typically, the temporal distribution of larval abundance was skewed, with a rapid increase to a maximum followed by a slower decline. This skewed density distribution results in a sigmoid-shaped cumulative distribution where the time of peak abundance is the time at which the inflection point of the sigmoid occurs. The Gompertz growth function (Draper and Smith 1981) was chosen to describe the cumulative distribution of the abundance data because the inflection point of this function is not constrained to the central point of the sigmoid curve. The form of the Gompertz function used was:

$$C_t = \alpha(\exp[-\beta e^{-\kappa t}]) \quad (4)$$

where C_t = cumulative density at time t

α = total or asymptotic cumulative density

β = location parameter

κ = shape parameter

t = time in days since February 15

The origin of the time scale for our data was set to the 15th of February, which is when winter flounder larvae generally first appear in the Niantic River. Least-squares estimates and asymptotic 95% confidence intervals for these parameters were obtained by fitting the above equation to the cumulative abundance data (based on the weekly geometric means) using nonlinear regression methods (SAS Institute 1985).

The derivative of the Gompertz function with respect to time yields a "density" function which directly describes the larval abundance over time (abundance curve). This density function has the form:

$$d_t = \alpha\beta\kappa(\exp[-\kappa t\{-\beta e^{-\kappa t}\}]) \quad (5)$$

where d_t = density at time t

and all the other parameters are the same as in Equation 4, except for α, which was rescaled by a factor of 7 because the cumulative densities were based on weekly geometric means and thus accounted for a 7-day period. Time of peak abundance was estimated as the date t_i corresponding to the inflection point of the function defined by its parameters β and κ as:

$$t_i = \frac{(\log_e \beta)}{\kappa} \quad (6)$$

The α parameter was used as an index to compare annual abundances. The κ parameter was used to compare the steepness of the abundance curve (Equation 5), where κ increases as the peak of the curve increases.

Winter flounder larvae were reared in the laboratory during 1986 to determine growth rates at various temperature regimes. Eggs were stripped from a female and fertilized with milt from two males. Larvae that hatched within 24 hours of each other were placed in 39-L aquaria held in a water bath. The water temperature in each regime was gradually increased during the holding period to mimic the seasonal temperature increase during larval winter flounder development. Photoperiod was similar to natural conditions. Larvae were fed rotifers (*Brachionus plicatilus*) and brine shrimp nauplii (*Artemia salina*) *ad libitum*. Known-age larvae were routinely sacrificed and measured to the nearest 0.1-mm standard length to obtain information on growth rate. For comparisons with other laboratory growth studies on larval winter flounder, length was converted to weight (μg) by the length-weight relationship of Laurence (1979):

$$\text{weight} = 0.045(\text{length})^{4.769} \quad (7)$$

and daily specific growth rates (SGR) were determined by:

$$SGR = 100 \frac{(\log_e wt_2 - \log_e wt_1)}{(t_2 - t_1)} \quad (8)$$

with t_1 and t_2 = first and last days of observation

wt_1 and wt_2 = weight at days t_1 and t_2, respectively

Annual entrainment estimates were calculated from data collected at station EN in addition to using these data to describe the abundance of winter flounder in Niantic Bay. The estimates were computed as the median density (number per 500 m^3) during the larval season times the total number of 500 m^3 units of seawater withdrawn by MNPS during the same period of time. A nonparametric method (Snedecor and Cochran 1967) was used to construct a 95% confidence interval around each median and corresponding entrainment estimate.

Post-larval young-of-the-year studies

A quantitative study of post-larval young-of-the-year winter flounder in the Niantic River began in 1983 (NUSCO 1987). Station LR has been sampled every year and WA since late 1984 (Fig. 1). Each station was visited once every week from late May through late September or early October during daylight within about 2 hours before to 1 hour after high tide. A 1-m beam trawl with interchangeable nets of 0.8-, 1.6-, 3.2-, and 6.4-mm bar mesh was used to catch young winter flounder. Two tickler chains were added in late June of 1983 to increase catch efficiency as older and larger young apparently were able to avoid the net without them (NUSCO 1987). In 1983, triplicate tows were made using one of the nets, which was changed as young grew during the season. Since 1984, two nets of successively larger mesh were used during each sampling trip to collect the entire available size range of young. A change to the next larger mesh in the four-net sequence was made when young had grown enough to become susceptible to it; the larger meshes reduced the amount of detritus and algae retained. Two replicates with each of the two nets were made at both stations and the nets were deployed in a random order. Distance was estimated by letting out a measured line attached to a lead weight as the net was towed at about 25 m per min. Tow length was increased from 50 to 75 to 100 m as the number of fish decreased throughout the summer of each year. For data analysis and calculation of CPUE, the catch of both nets used at each station was summed and standardized to give a density per 100 m^2 of bottom covered by the beam trawl. For comparisons among years, a moving average of three weekly density estimates was used to smooth the trends in abundance over time.

The young winter flounder collected were measured in the field or laboratory to the nearest 0.5 mm in total length (TL). During the first few weeks of study, standard length (SL) was also measured because many of the specimens had damaged caudal fin rays and total length could not be taken. A relationship between the two lengths determined by a functional regression (NUSCO 1987) was used to convert SL to TL whenever necessary.

To calculate mortality rate, all young were assumed to comprise a single cohort. A catch curve was constructed with the natural logarithm of density plotted against time in weeks. The slope of the descending portion of the curve provided an estimate of the weekly rate of instantaneous mortality (Z). Once Z was determined, weekly survival rate (S) was estimated as exp(-Z) and monthly as exp((-Z)(30.4/7)).

Impingement of winter flounder at MNPS

The number of winter flounder impinged on the traveling screens of MNPS Unit 2 was estimated using techniques described in the Fish Ecology section of this report. Length-frequency

TABLE 1. Annual mark and recapture data from Niantic River adult winter flounder abundance studies during the spawning season from 1976 through 1987.

Year	Dates sampled	Number of weeks	Number marked[a]	Number recaptured	% recaptured
1976	March 1 - April 13	7	6,479	453	7.0
1977	March 7 - April 12	6	3,737	257	6.9
1978	March 6 - April 25	8	4,417	360	8.2
1979	March 12 - April 17	6	4,067	241	5.9
1980	March 17 - April 15	5	4,313	433	10.0
1981	March 2 - April 14	7	6,726	469	7.0
1982	February 22 - April 6	7	5,795	270	4.7
1983	February 21 - April 6	7	5,196	363	7.0
1984	February 14 - April 4	8	3,740	197	5.3
1985	February 27 - April 10	7	3,024	170	5.6
1986	February 24 - April 8	7	2,790	175	6.3
1987	March 9 - April 9	5	2,334	133	5.7

[a] Minimum size for marking was 15 cm during 1976-82 and 20 cm thereafter.

data of impinged fish were also available. Routine impingement monitoring was discontinued in mid-December 1987, upon agreement between NU and CT DEP.

Results and Discussion

Adult and juvenile studies

Abundance of winter flounder near Millstone

The Niantic River winter flounder population is demographically open and therefore subject to immigration, emigration, natural death, and removal by fishermen (White et al. 1982). Mark and recapture surveys designed to estimate abundance of open populations using the stochastic model of Jolly began in 1976 (NUSCO 1987). The Jolly model is an extremely powerful general formula that uses all the information provided by the mark and recapture experiment and provides the most efficient abundance estimates for open populations as long as basic assumptions are approximately met (Cormack 1968; Southwood 1978; Begon 1979). Application of the Jolly model to the Niantic River winter flounder population was discussed previously in NUSCO (1986a, 1987).

The 1987 survey had the latest start since 1980 due to extended ice cover in the river, which resulted in only 5 weeks of sampling (Table 1). Although the percentage of recaptures (5.7%) was similar to the range observed during 1982-86 (4.7-7.0%), fewer fish were marked than in any previous year. A condition peculiar to 1987 was the large amount of kelp and detritus found in the mid to lower river channel (stations 2 and 4), which entirely precluded sampling at the latter station after the first week of study. During most of the year, few winter flounder were found in the navigation channel (stations 1 and 2) and catch in the basin of the upper river (station 51) was also less than in previous years; most fish were in the western arm of the river (stations 52-54). However, during the fourth week of the survey, many fish withdrew from the upper river arm into the basin following a storm.

For the 1987 survey, log-likelihood ratio tests indicated no significant differences in the proportions of marked and recaptured fish classified by

sex or length. The percentages of fish recaptured at stations 51 (9.6%) and 52 (8.1%) were significantly greater than those at the other stations (2.5-3.9%). In most other years when significant differences were found, greatest percentages of recaptures were from the lower river stations (1 or 2), most likely because any marked winter flounder moving out of the river would have had a greater probability of being caught near its mouth.

TABLE 2. Weekly catch data used for estimating the Jolly index of winter flounder abundance during the spawning season in the Niantic River.

Week no.	Date-week of	Total catch	No. unmarked	No. marked	No. removed	No. examined	Recaps. 1981-86	Recaptures (week marked)					Total recaps
								1	2	3	4	5	
1	3-9	990	269	720	1	721	37	-					-
2	3-16	686	231	455	0	455	19	22	-				22
3	3-23	804	200	604	0	604	26	21	13	-			34
4	3-30	941	385	555	1	559	27	13	13	22	-		48
5	4-6	661	661	-	0	372	14	3	2	7	17	-	29
Total		4,082	1,746	2,334	2	2,711	123	59	28	29	17	-	133

Using the methodology previously described, annual Jolly composite abundance indices were calculated to describe relative abundance of winter flounder in the Niantic River during the spawning season. The weekly catch data (Table 2) were used with the Jolly model and the computed 1987 index of abundance was 10.0 ± 3.8 (Table 3). This represents a slight increase over the 1986 index, which was a 12-year low (Table 4; Fig. 3). Sampling intensities must be relatively high to obtain acceptable estimates of Jolly model parameters (Cormack 1979; Buckland 1980; Nichols et al. 1981; Hightower and Gilbert 1984). Estimates of population size (N) are biased to some degree and for sampling intensities of 5 to 9% (which is similar to the Niantic River studies), N may have low accuracy, depending upon the absolute population size (Gilbert 1973; Carothers 1973; Hightower and Gilbert 1984). Examination of simulations done by Hightower and Gilbert (1984) indicated that Jolly abundance estimates of Niantic River winter flounder may have been accurate to

TABLE 3. The Jolly index of abundance for winter flounder larger than 20 cm during the 1987 spawning season in the Niantic River.

Date-week of	Jolly estimate (N)	Standard error of N	Probability of survival (Φ)	Standard error of Φ	Calculated no. joining (B)	Standard error of B
3-9			0.866	0.203		
3-16	12,890	4,005	0.644	0.179	3,780	2,864
3-23	12,074	3,494	0.354	0.127	878	1,122
3-30	5,154	1,835				

1987 Jolly index estimate = 10.0 ± 3.8

TABLE 4. Annual Jolly composite index of winter flounder abundance during the spawning season in the Niantic River from 1976 through 1987.

Year	Number of values used	Composite index ±2 standard errors[a]	Adjusted index[b]
1976	3	21.8 ± 4.8	---
1977	3 [c]	18.2 ± 5.1	---
1978	3 [d]	14.6 ± 3.5	---
1979	2 [d]	18.7	---
1980	3 [d]	18.2 ± 4.0	---
1981	3	28.7 ± 6.6	---
1982	3	49.4 ± 16.7	---
1983	3	29.9 ± 7.0	35.0
1984	3	29.3 ± 10.5	36.3
1985	3	21.6 ± 9.3	26.2
1986	3	8.3 ± 2.7	9.7
1987	3 [d]	10.0 ± 3.7	11.9

[a] For winter flounder larger than 15 cm during 1976-82 and 20 cm thereafter. Index adjusted to all fish larger than 15 cm for 1983-86.

[b] Index adjusted to all fish larger than 15 cm for 1983-87 for comparison with 1976-82.

[c] Only N_1 excluded.

[d] No values of N excluded.

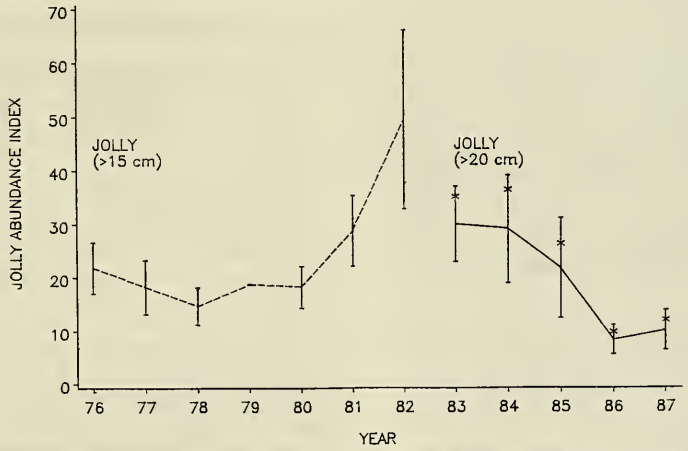


Fig. 3. Jolly index of abundance (±2 standard errors) for Niantic River winter flounder larger than 15 cm from 1976 through 1982 and larger than 20 cm from 1983 through 1987. For comparisons, the CPUE index was adjusted upwards by adding fish between 15 and 20 cm during 1983-87 (shown by a *).

within ±50% of actual values. As population size decreases, as it has in recent years, accuracy decreases and abundance estimates may become negatively biased.

A second, and perhaps less biased, measure of abundance for winter flounder was the CPUE during a 4-week period from mid-March through early April, the only period which included comparable data for all annual surveys. The median CPUE was used as the most appropriate catch statistic because the trawl catch data were not normally distributed and were positively skewed. A δ-mean CPUE was used as an index of abundance for other trawl data sets where the data series had zero observations. However, the Niantic River abundance surveys had only a few tows without fish throughout the past 12 years. A comparison of the two indices showed that they were highly correlated for winter flounder both larger and smaller than 15 cm (Spearman rank-correlation, $r = 0.96$ and 0.98, respectively). Therefore, the median CPUE was retained as the best measure of abundance for the Niantic River spawning stock.

The 1987 median CPUE of 13.7 was similar to the 1986 value of 12.0 (Table 5; Fig. 4). Mean tow duration and catch of winter flounder from tows of one-half (n = 2; 6.6 min; 6.0 fish) and two-thirds (n = 79; 7.8 min; 11.3 fish) of the standard tow were reasonably proportional to those for the regular distance of 0.55 km (n = 137; 12.1 min; 18.2 fish) and shorter tow length did not affect the calculation of median trawl CPUE in 1987. Annual trends in median CPUE generally corresponded with the Jolly composite index of abundance until 1982. The CPUE in 1982 (42.6) was nearly the same as in 1981 (43.4), but the Jolly abundance index increased 72% (28.7 to 49.4). However, the latter 1982 estimate had a large confidence interval (±16.7). The decline in CPUE for fish larger than 20 cm from 1983 (22.1) to 1984 (12.8) and 1985 (12.6) was greater than for the Jolly abundance index (29.9 to 29.3 and 21.6). The Jolly index for 1986 (8.3) decreased more than 60% relative to 1985, but the CPUE decreased by only about 20%. Both the Jolly index and CPUE showed similar increases (22% and 14%, respectively) in 1987. The CPUE for 1984-87 indicated population levels about one-half of those during 1976-80, which also contradicted the Jolly abundance indices. These differences between abundance indices and biases of both were discussed at length in NUSCO (1987).

TABLE 5. Median CPUE of Niantic River winter flounder larger than 15 cm from 1976 through 1987 during the period of mid-March through mid-April.

Year	Total tows made	Tows used for CPUE	% of tows used	Median CPUE	95% confidence interval	Coeff. of skewness[a]
1976	112	85	76	28.0	22.5-37.0	2.33
1977	154	123	80	24.0	20.0-30.0	1.45
1978	106	88	83	19.6	16.2-25.0	1.18
1979	93	77	83	26.8	22.4-38.4	1.67
1980	112	91	81	31.5	26.1-42.5	1.54
1981	109	97	89	43.4	36.2-51.4	1.24
1982	90	87	97	42.6	35.2-48.8	1.13
1983	135	134	99	30.8	24.1-33.9	0.96
1984	145	143	99	15.0	13.6-16.6	1.48
1985	156	155	99	14.7	12.7-15.0	1.13
1986	179	173	97	12.0	10.6-14.6	1.25
1987	198	197	99	13.7	12.4-15.3	0.59

[a] Zero for symmetrically distributed data.

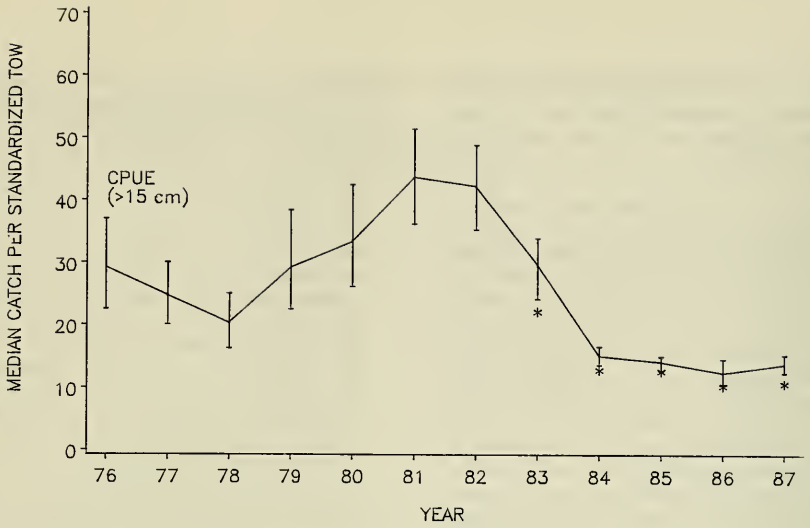


Fig. 4. Median trawl CPUE (±2 standard errors) for Niantic River winter flounder larger than 15 cm from 1976 through 1987. For comparisons with the Jolly index, the CPUE was adjusted downwards by deleting fish between 15 and 20 cm during 1983-87 (shown by a *).

The median CPUE of winter flounder smaller than 15 cm was calculated for fish taken during the adult winter flounder surveys in the Niantic River from 1976 through 1987. Nearly all of the fish in this size group were age 1 yearlings and represented the year-class spawned during the previous year. Data were restricted to the mid-March to mid-April period for comparability among years and to stations 1 and 2 because small winter flounder were less abundant than adults in the upper river. Inclusion of data from upper river stations could have biased inter-year comparisons because few or no tows were made there prior to 1981.

Juvenile catches were more variable than those of adults (Table 6). Abundance reached a peak during 1981 through 1983 (50.1-87.2), but fell to previous levels in 1984 (16) and 1985 (27.7). CPUE declined to 3.6 in 1986 and 5.5 in 1987. The small numbers of juveniles suggested poor reproductive success in recent years. However, this measure of winter flounder abundance may be affected by differential distribution of the juveniles. Unlike adults, juveniles do not necessarily enter the river during the spawning season and other factors, such as water temperature, may influence their movements. Although temperature is an important factor in winter flounder distribution, annual differences in late winter through early spring water temperature were not significantly correlated with abundance inside or outside of the river. During the past several years, juveniles have been found in greater numbers throughout the entire river. As their distribution in area increased, concentrations in the lower river most likely decreased. This confounded the use of an abundance index based on tows from only the lower river channel stations. Using data from the trawl monitoring program, a comparison between the number of juveniles inside and outside the river during the spawning period was made and is presented below.

TABLE 6. Median CPUE of Niantic River winter flounder smaller than 15 cm from 1976 through 1987 during the period of mid-March through mid-April (stations 1 and 2 only).

Year	Total tows made	Tows used for CPUE	% of tows used	Median CPUE	95% confidence interval	Coeff. of skewness[a]
1976	80	64	80	18.0	13.5-25.0	0.81
1977	143	116	81	25.5	18.0-30.9	1.10
1978	100	84	84	16.1	10.2-25.0	1.81
1979	79	71	90	27.0	17.4-42.3	1.88
1980	101	90	90	48.7	33.8-60.0	1.14
1981	47	45	96	87.2	61.0-120.9	0.67
1982	39	39	100	61.0	46.5-86.3	1.00
1983	44	44	100	50.1	32.8-61.2	0.58
1984	41	41	100	16.0	9.9-20.4	2.71
1985	48	48	100	27.7	20.9-41.1	1.00
1986	37	35	95	3.6	2.5-8.7	1.51
1987	33	33	100	5.5	3.4-7.4	2.00

[a] Zero for symmetrically distributed data.

An annual δ-mean CPUE was computed for winter flounder of all sizes taken throughout the year (January-December) at all stations sampled by the trawl monitoring program. This period represented a change from previous reports, where an October-September year was defined. Using a calendar year allowed for direct comparisons with other regional indices of abundance. Neither period had particularly strong biological meaning; the winter flounder was ubiquitous in the Millstone area and made up about 40% of the catch (ranked first) in the trawl monitoring program. The δ-mean CPUE index showed a pattern of fluctuating abundance (Fig. 5). However, it differed in several respects from the median CPUE for the Niantic River spawning stock. The peak in δ-means persisted from 1979 through 1983 and was not as pronounced as it was for the Niantic River medians, which were highest in 1981 and 1982 (Fig. 4). Abundance, as measured by the δ-mean for 1985 and 1986 was greater than that for 1977 and 1978, whereas the median CPUE for the Niantic River spawning stock in recent years has been smaller than that during the 1970s.

Although the trawl monitoring program catch included winter flounder of all sizes, fish larger than 15 cm made up about two-thirds of the catch; annual percentages ranged from 55% in 1983 to 75% in 1976. On a monthly basis, larger fish comprised 76 to 92% of the catch from June through November. Small (< 15 cm) fish made up two-thirds of the area-wide total from January through March as larger fish congregated on the spawning grounds. Approximately equal numbers of small and large fish were taken in April, May, and December. Based on electrophoretic studies, there was most likely a mixture of stocks present at the trawl stations outside of the Niantic River, except for the spawning season (NUSCO 1987).

A comparison of the trends in abundance of small and large winter flounder taken by the trawl monitoring program during January through April (except station NR) was made with the catch of similar-sized fish during the annual population surveys in the river. This period was chosen because it overlapped the spawning period and the Niantic River station was eliminated because catches in the river were used for the determination of the winter flounder survey median. On the basis of the overlapping 95% confidence intervals, there was little difference among the numbers of larger winter flounder at stations outside the river; catches remained at a low and stable level of

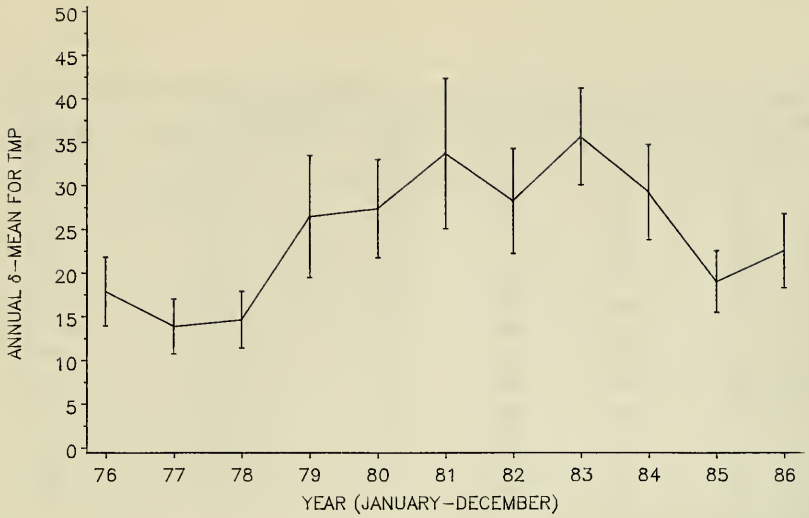


Fig. 5. Annual δ-mean CPUE (±2 standard errors) for winter flounder taken by the trawl monitoring program (TMP) from January 1976 through December 1987.

about 5 fish a tow (Fig. 6). This was in contrast to the large fluctuations in abundance seen within the river.

Catch of juveniles (< 15 cm) in winter and early spring also fluctuated less outside than inside the river. As the number of small fish in the river declined to low levels in 1986 and 1987, the number outside increased in respect to 1984 and 1985 and was at levels of abundance seen from 1976 through 1982 (Fig. 7). This was an important finding, as the very low abundance of juvenile fish in the river in recent years seemingly pointed towards continued declines in an already reduced adult stock. However, the greater catches in the much larger area outside of the river suggested that the year-class strength for 1986 and 1987 in the general area may not have been as low as catches during the winter flounder survey would have indicated, assuming that many of these fish were produced in the Niantic River. The differential distribution and abundance of juveniles during the trawl surveys has made it difficult to predict future adult population size in the Millstone area.

Regional and historical trends in abundance

The abundances of winter flounder for the Niantic River population surveys and from the trawl monitoring program was compared to other regional indices (Table 7). With a few exceptions, most indices were significantly correlated and thus described real trends in abundance that occurred throughout Southern New England. One exception was the previously mentioned lack of correspondence between the two Millstone series. However, the Niantic River adult median CPUE was significantly correlated with several other measures of adult stock size. These included two commercial fishing CPUE indices for Rhode Island and one for Connecticut (Fig. 8) In addition, the Niantic River annual medians were correlated with the URI trawl survey annual δ-mean, lagged

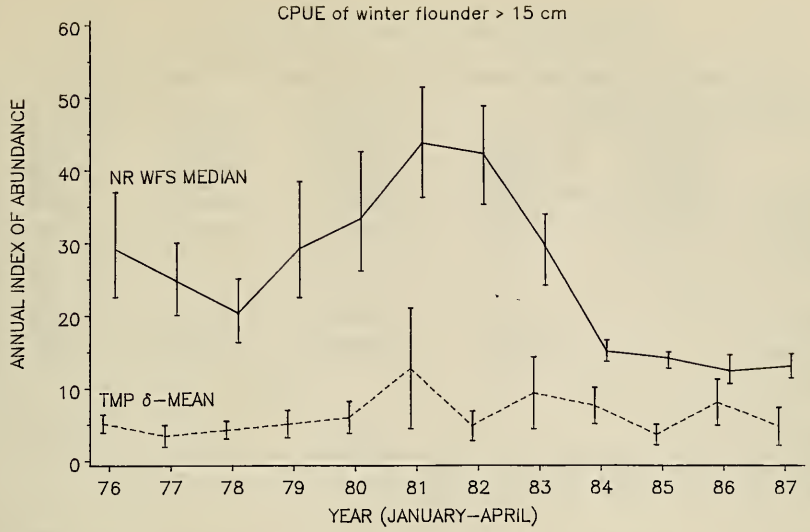


Fig. 6. Comparison of annual January-April δ-mean CPUE for the trawl monitoring program (TMP) with the Niantic River survey median (WFS) for winter flounder ≥ 15 cm from 1976 through 1987.

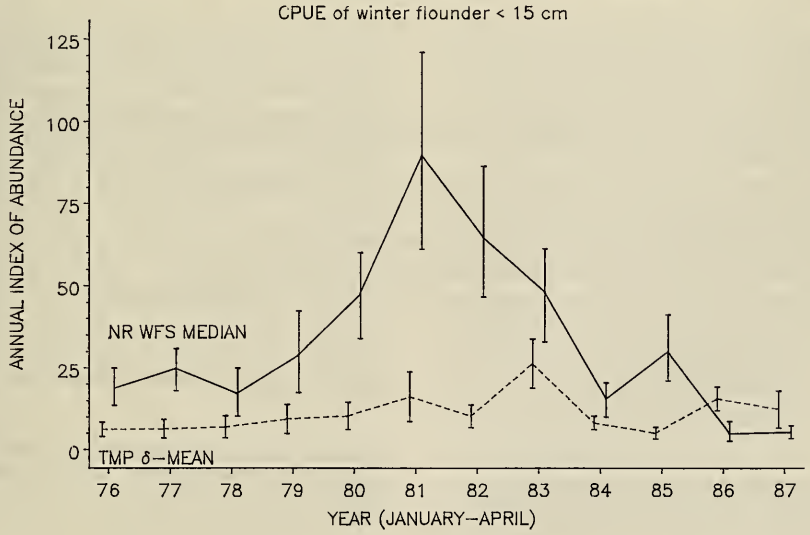


Fig. 7. Comparison of annual January-April δ-mean CPUE for the trawl monitoring program (TMP) with the Niantic River survey median (WFS) for winter flounder < 15 cm from 1976 through 1987.

TABLE 7. Matrix of Spearman's rank-order correlations for various Southern New England winter flounder abundance indices from 1964 through 1987.

Source	NMFS "Red Book" (1964-87)[a]	NMFS Area 539 (1964-87)[b]	Connecticut DEP (1979-87)[c]	URI trawl survey (1966-86)[d]	Millstone trawl survey (1976-86)[e]
Niantic River	0.6853 [g]	0.7552	0.8034	0.6224	0.5000
adult survey	0.0139 *	0.0045 **	0.0091 **	0.0307 *	0.1173 NS
(1976-86)[f]	12	12	9	12	11
NMFS		0.7332	0.5858	0.6844	0.7546
"Red Book"		0.0001 **	0.0974 NS	0.0006 **	0.0073 **
landings		24	9	21	11
NMFS			0.7364	0.8347	0.8000
Area 539			0.0237 *	0.0001 **	0.0031 **
landings			9	21	11
Connecticut				0.5105	0.5749
DEP commercial				0.1603 NS	0.1361 NS
trawl landings				9	8
University of					0.6364
Rhode Island					0.0353 *
trawl survey					8

[a] National Marine Fisheries Service "Red Book" commercial landings annual CPUE for Rhode Island (lbs/50-ton unit).

[b] National Marine Fisheries Service annual CPUE for statistical area 539 (lbs/directed trip).

[c] Connecticut DEP-licensed commercial trawler CPUE (lbs/trawl-hr).

[d] University of Rhode Island annual δ-mean trawl CPUE (advanced 1 year for comparisons).

[e] NU trawl monitoring program annual δ-mean trawl CPUE for all winter flounder.

[f] Niantic River winter flounder survey median trawl CPUE for adult (≥ 15 cm) winter flounder.

[g] Shown for each Spearman rank-order correlation:

correlation coefficient

probability level, where NS - not significant, * - significant at $p \leq 0.05$, ** - significant at $p \leq 0.01$

number of observations

1 year. Similarly, the annual δ-means for the trawl monitoring program were significantly correlated with the three Rhode Island indices. Since larger fish made up one-half to three-quarters of the catch in the Millstone trawl survey, no lags were used for the comparisons.

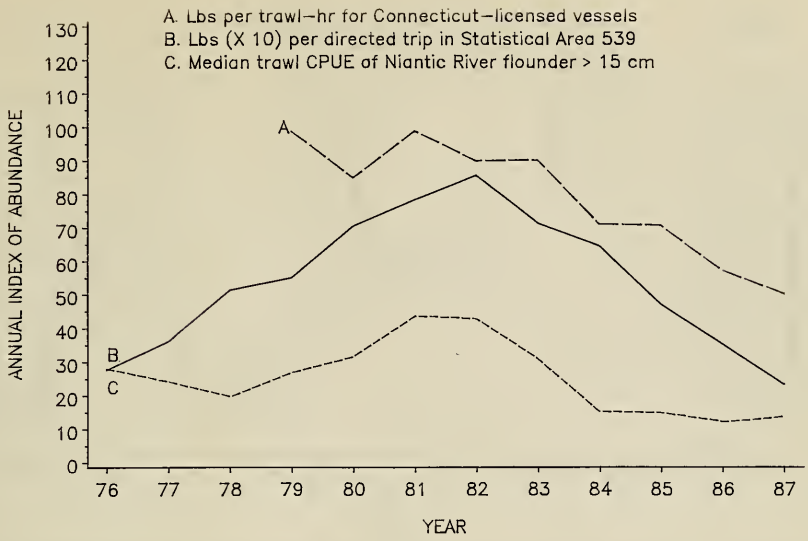


Fig. 8. Comparison of annual winter flounder CPUE for Connecticut-licensed trawlers, NMFS Statistical Area 539, and Niantic River abundance surveys from 1976 through 1987.

The Rhode Island indices represented the longest time-series of available data, with one set of statistics going back to 1947. These data illustrated the inherent variability typical for winter flounder abundance (Fig. 9). Numbers were relatively high from the mid-1950s through the early 1970s, with several sharp increases in commercial catches most likely related to the occurrence of particularly large year-classes. Abundance declined in the mid and late 1970s, but another large year-class was produced in 1978. This year-class, along with better-than-average recruitment in 1979 and 1980, resulted in the winter flounder abundance peak seen during the early 1980s. The recent declining trend has reduced winter flounder to levels at or below those found in the early 1950s and early 1970s.

Perlmutter (1947) presented a brief history of the winter flounder fishery in New England and New York from its beginning in the late 1800s to the 1940s. His work was prompted by a decline in catches in the late 1930s and 1940s, compared to peak years of the fishery in 1928-31. He noted considerable fluctuation in commercial fishing CPUE from 1910 through 1947. For example, catch-per-fyke-net at both Boothbay Harbor, ME and Woods Hole, MA was very high during the startup of the fishery in the early part of this century and relatively high from 1925 through 1933. However, catches decreased about 30-40% during 1934 to 1940. Introduction of more efficient gear (change from fyke nets to beam trawls to otter trawls) and vessels (sail to engines) as well as increased market demand allowed for the full development of the fishery and increasing exploitation of the stocks. The increase in relative fishing power has undoubtedly continued through the present with the addition of electronics and other fishing aids in response to market demand and high prices.

Perlmutter (1947) also provided logbook data for a Connecticut trawler working in Fishers Island Sound. The catch-per-trawl-day (average daily hours fished not given) from 1930 through

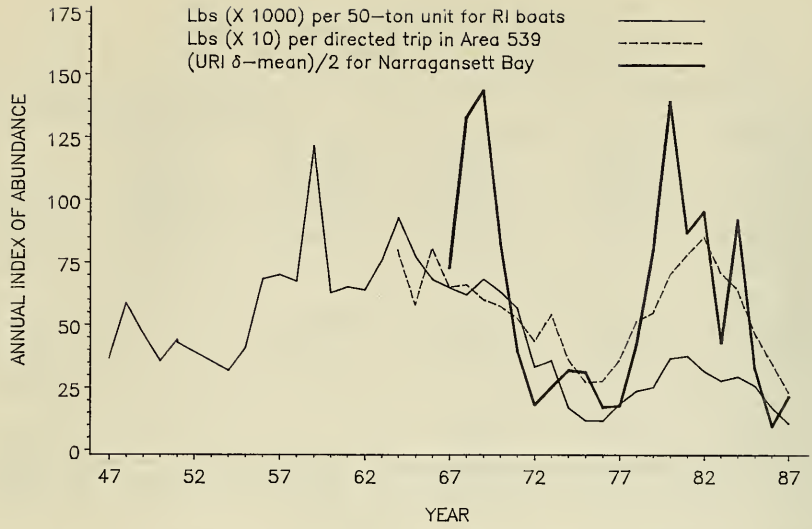


Fig. 9. Comparison of annual winter flounder CPUE for Rhode Island trawlers, NMFS Statistical Area 539, and the URI Narragansett Bay trawl survey from 1947 through 1987.

1941 ranged from 402 to 853 lb, with largest catches made in the early 1930s when winter flounder were most abundant. In recent years (1979-87), catch-per-trawl-day for all Connecticut-licensed trawlers was calculated (from CT DEP, unpublished data) to have been from 315 to 521 lbs (average of 5 hours fished per day). The highest daily rate occurred in 1983, when winter flounder were most available, and lowest rates were in 1986-87. Despite the recent decline in winter flounder abundance and commercial trawler CPUE, landings have remained relatively high in Connecticut (Fig. 10) because of greater effort, with increases seen in mean days fished, mean hours trawled, and mean hours per day of fishing (Table 8). In addition, an increasing proportion of the catch was sustained by fish taken in eastern Connecticut waters from the mouth of the Connecticut River to the Rhode Island border (Fig. 11).

Commercial landings elsewhere in New England have recently decreased. Despite the declining resource, high landings in Massachusetts have been maintained by increasing effort and the number and percentage of small fish landed (MDMF 1985). NMFS (1987) reported that in each of the three major stock assessment geographical areas (Southern New England-Middle Atlantic, Gulf of Maine, Georges Bank) winter flounder abundance decreased to historical low levels in 1986, with declines in commercial landings generally reflecting assessment survey CPUE indices.

In conclusion, the fluctuations in abundance seen for Niantic River winter flounder have occurred concurrently with other populations in New England. Examination of long time-series of abundance data showed that winter flounder numbers have fluctuated throughout this century, with production of several large year-classes that resulted in periods of peak abundance. These events have been viewed by some as the result of favorable environmental conditions during periods of reproduction and early life history (Jeffries and Johnson 1974; McHugh 1977; Jeffries and Terceiro 1985).

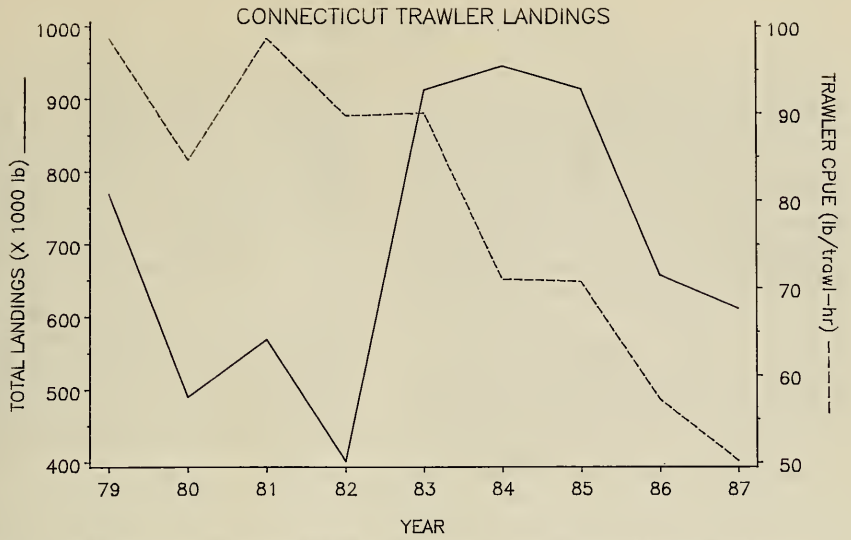


Fig. 10. Comparison of Connecticut total annual winter flounder landings with trawler CPUE from 1979 through 1987.

TABLE 8. Connecticut-licensed trawler commercial fishing statistics for winter flounder from 1979 through 1987 (derived from unpublished data provided by CT DEP).

Year	Total pounds landed	Total days fished	Hours trawled	Average days fished	Average hours trawled	Average hours per day	Pounds per trawl-hr	Pounds per trawl-day
1979	768644	1644	7691	16.6	76.8	4.6	98.6	456
1980	489419	1411	5604	11.8	46.6	4.0	84.6	336
1981	568463	1311	5549	14.4	61.0	4.2	98.6	417
1982	401061	1024	4377	10.6	45.1	4.3	89.7	381
1983	911694	1736	10058	15.9	92.3	5.8	90.0	521
1984	944381	2184	12700	20.0	116.5	5.8	70.9	413
1985	912685	2089	12469	18.9	112.3	6.0	70.6	421
1986	657221	1185	11188	20.1	119.0	5.9	57.2	340
1987	611428	1938	11993	20.6	127.6	6.2	50.2	315

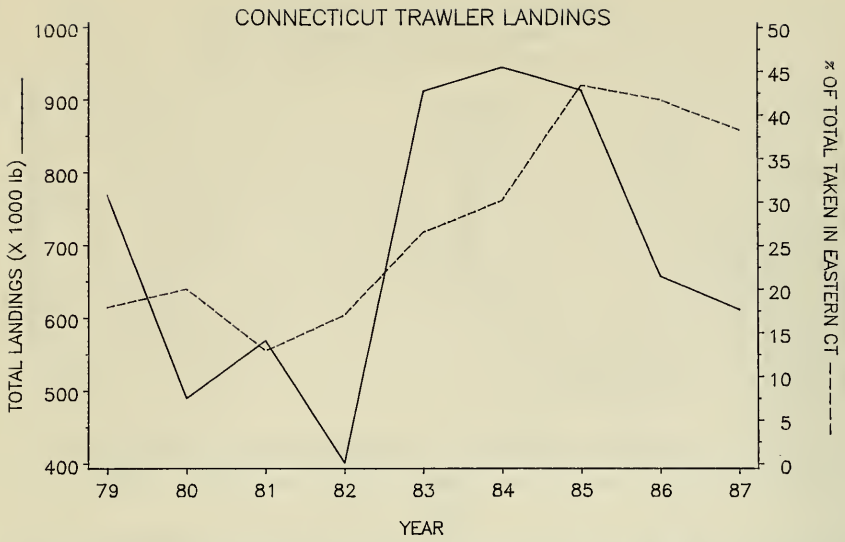


Fig. 11. Comparison of the total annual winter flounder landings with the percentage taken in eastern Connecticut from 1979 through 1987.

Reproduction

The sex ratio of winter flounder larger than 20 cm during the spawning season in the Niantic River ranged from 0.78 to 2.03 females for each male during the past 11 years (Table 9). The geometric mean was 1.33, but the last 2 years were the only ones in which more males than females were taken. This was unusual, based on past ratios in the river and reported ratios of 1.50 to 2.33 in favor of females by Saila (1962a, 1962b) and Howe and Coates (1975) for other populations in southern New England. The reduced number of females may have resulted from increased fishing pressure on females. They are larger than males and tend to move longer distances away from the Millstone area (NUSCO 1987), which could have increased their vulnerability to offshore commercial fisheries.

TABLE 9. Female to male sex ratios of winter flounder taken during the spawning season in the Niantic River from 1977 through 1987.

	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	Geometric mean
All fish captured	1.03	2.23	1.37	2.66	1.42	1.16	1.52	1.07	1.37	0.92	0.78	1.32
Measured fish > 20 cm	1.26	1.95	1.21	2.03	1.61	1.50	1.52	1.07	1.37	0.92	0.78	1.33

Female winter flounder can become sexually mature when they are age 3 or when about 20 cm in length; northerly populations mature at smaller sizes and older ages than in Southern New England (Dunn and Tyler 1969; Dunn 1970; Kennedy and Steele 1971; Beacham 1982). Re-

sults of a probit analysis showed that the length of 50% sexual maturation of Niantic River females during 1981-87 was 26.8 cm with a 95% confidence interval of 26.3 to 27.2 cm. On an annual basis, values ranged from 25.1 cm in 1983 to 29.4 cm in 1981; most of these fish were 3 or 4 years old. Based on our observations, many males mature at even smaller sizes (10-12 cm) and younger ages (2 years) than females.

Winter flounder spawning was followed by noting the weekly change in the percentage of gravid females larger than 25 cm in the Niantic River. Generally, most spawning was completed by late March or early April as relatively few gravid females remained in the river (Fig. 12). Ice in the river prevented starting population surveys earlier in January or February, so for most years approximately two-thirds of the females examined during late February or early March had spawned before sampling began. In most cases, spawning appeared to be correlated with water temperature. In relatively cold years, proportionately fewer females spawned during the earlier portion of the survey, whereas in warmer years more were spent at the beginning of sampling (NUSCO 1987).

The annual proportion of females larger than 26 cm was used with the Jolly index of abundance for that year to obtain a relative index of female spawners. Spawning females made up 20 to 51%

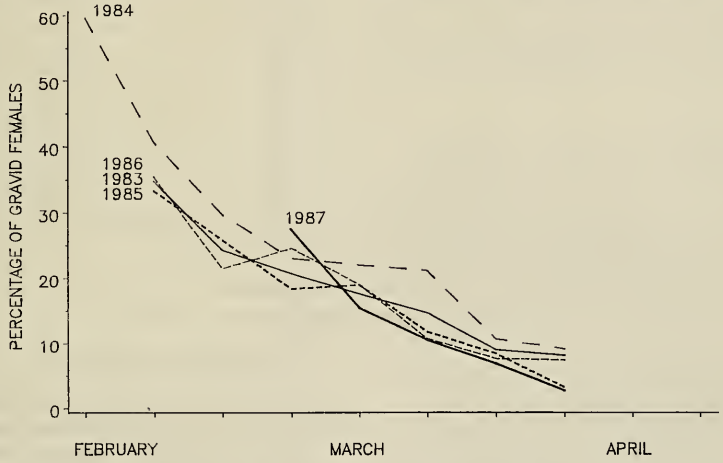


Fig. 12. Percentage of adult female winter flounder in spawning condition by week in the Niantic River from 1983 through 1987.

of the population during the past 11 years (Table 10). Percentages for 1977-82 were lower because they were based on abundance estimates for all fish larger than 15 cm and thus included more immature fish in the total. The value for 1980 (20%) was particularly low and was an indication that comparatively more small, immature fish were caught during that survey.

Annual average fecundity estimates were calculated using a length-fecundity relationship described in NUSCO (1987) with annual length-frequency data. Values have been relatively consistent with somewhat greater averages found since 1982, when the start of the surveys was advanced into February. During the past several years, most females larger than 40 cm were found

in the Niantic River early in the season and many left the estuary in March. Surveys during earlier years started after February and missed many of these large winter flounder, resulting in lower averages. The mean length of all females 20 cm and larger in 1980 was only 29.7 cm, in comparison to 31.4 to 32.1 cm for 1979 and 1981-85, respectively. This was additional evidence that fewer large females were sampled during the 1980 survey. In contrast, the means of 33.4 cm in 1986 and 32.8 cm in 1987 were particularly large, indicating that along with decreasing abundance, the female population included more larger and older specimens than in previous years.

TABLE 10. Annual indices of female spawners and egg production for Niantic River winter flounder from 1977 through 1987.

Year	Relative index of spawning females[a]	% of population comprised by mature females[b]	Average fecundity ($x10^5$)	Relative index of egg production[c]
1977	5.6	31	4.8	2.69
1978	5.5	38	5.1	2.81
1979	4.8	26	5.3	2.55
1980	3.7	20	4.7	1.70
1981	10.7	37	5.3	5.66
1982	18.9	38	5.7	10.79
1983	15.2	51	5.6	8.51
1984	12.6	43	5.7	7.20
1985	10.1	47	5.9	5.92
1986	3.5	43	6.5	2.31
1987	4.0	40	6.1	2.46

[a] From Jolly index of abundance and percentage of mature females, assuming that all females 26 cm and larger were mature.

[b] For winter flounder larger than 15 cm during 1976-82 and 20 cm thereafter.

[c] A relative index for year-to-year comparisons and not an absolute estimate of production.

Relative egg production indices were determined using Jolly abundance indices with the length, maturity, and fecundity data. Since the indices reflect both annual average fecundity and abundance, the value for 1980 was probably underestimated. The egg production index peaked in 1982 and declined about 80% since then as the increase in average fecundity was not large enough to offset declines in abundance of adult females. However, adult abundance and absolute egg production alone were not necessarily the most important factors determining year-class strength (i.e., production of young in a particular year). This is discussed further in the following section.

Stock and recruitment

Although not overly long in comparison to data sets typically used in stock assessment studies, the 12 years of abundance estimates for the Niantic River winter flounder allowed for the investigation of a relationship between adult stock size and the number of offspring they produced. This relationship, termed stock and recruitment, has been described in various forms (e.g., Ricker 1954; Beverton and Holt 1957; Cushing 1973; Shepherd 1982). The parameter estimates of a stock and recruitment model may be used in other fisheries models (e.g., to predict future yields) or, more specifically for MNPS studies, in the stochastic population dynamics impact assessment

model. In the following discussion of the model, the recruitment index was determined as the fraction that age 3 (21.4-28.0 cm) fish made up of each annual Niantic River adult CPUE. These lengths represented the midpoints of the 10th and 90th percentiles of length between ages 2 and 3 and ages 3 and 4, respectively. The index of age 3 fish was multiplied by a scaling factor (1.938) reflecting their lifetime reproductive contribution (maximum life span was assumed to be 12 years). Age 3 fish were used as the best estimate of recruitment since a majority of them were mature and in the Niantic River for spawning each year. This also extended the period of compensatory mortality throughout the entire period of immaturity without restricting it to a particular larval or juvenile life stage. The index of parental stock producing the age 3 fish was the fraction of each annual CPUE made up by all adults age 3 and older (≥ 21.4 cm) during the spawning season 3 years prior to the age 3 recruitment estimate.

Jones (1982) noted that the largest stock abundances for a number of species were usually about three to six times that of the smallest ones and that the difference between them usually approximated the mean. Ursin (1982) reported that recruitment variation over 13 years for the North Sea plaice (*Pleuronectes platessa*), which is an European flatfish closely related to the winter flounder (Burton and Idler 1984), varied by a factor of five from the smallest to the largest year-class. Many other species, such as cod (*Gadus morhua*) and herring (*Clupea harengus*), also had ratios of this order. However, a few fishes (e.g., haddock, *Melanogrammus aeglefinus*) varied by a factor of 100 or more, suggesting the lack of a stabilizing mechanism for recruitment. For the Niantic River parental stock index, the range seen from 1976 through 1987 was 10.2 to 32.3 (difference of 22.1) with a mean of 19.0. This suggested that our stock and recruitment data set probably included representative small and large stock sizes typical for this population. The two Rhode Island commercial fishing indices had ratios of abundance that were 4 and 11 and the URI series had a difference of 15. However, the former may have been influenced by economic and social factors and the latter time-series included many juveniles, which, as illustrated by our data, can be quite variable in number and may not absolutely reflect true abundance.

A plot of recruit versus parental indices suggested a dome-shaped curve with reduced recruitment at high levels of adult abundance. This is typical for fishes with high fecundity (Cushing 1971; Cushing and Harris 1973), although the reliability of this relationship will be ascertained as more data are collected. Because a dome was presumed for the stock-recruitment data, Ricker's (1954, 1975) model was fit to the data. His two-parameter (α and β) model did not explain much ($R^2 = 0.44$) of the variability seen in recruitment (Fig. 13). For example, the 1978 and 1984 year-classes were remarkably different, although produced by similar adult abundance.

Numerous examples have been given where recruitment success of a species has been strongly linked with environmental factors (Cushing 1973, 1977; Sissenwine 1974, 1977, 1984; Roff 1981; Shepherd et al. 1984; Lorda and Crecco 1987). In particular, water temperature has been found to be inversely related to strong year-classes of winter flounder in Rhode Island (Jeffries and Johnson 1974; Jeffries and Terceiro 1985; Gibson 1987). Roff (1981) also noted that abnormally cold temperatures have been related to strong year-classes in several other winter-spawning flatfishes. To examine possible temperature effects, yearly mean water temperatures during the winter flounder spawning and larval seasons (January-May) were calculated for single months and for various combinations of two or more months. For each month or group of months, deviations from the long-term mean were computed and compared to annual recruitment indices. The strongest negative correlation ($r = -0.78$) was found between February temperature deviations and recruitment indices (Fig. 14). Correlations between recruitment and March and February-March temperatures were also significant.

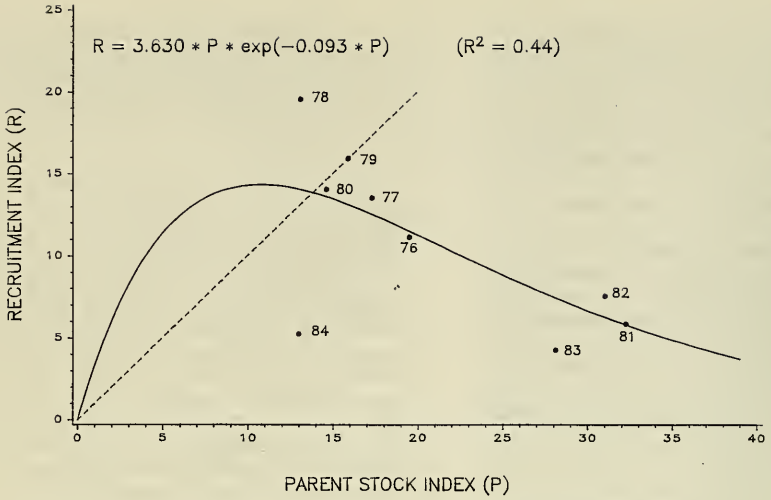


Fig. 13. Stock-recruitment model (two-parameter) for Niantic River winter flounder.

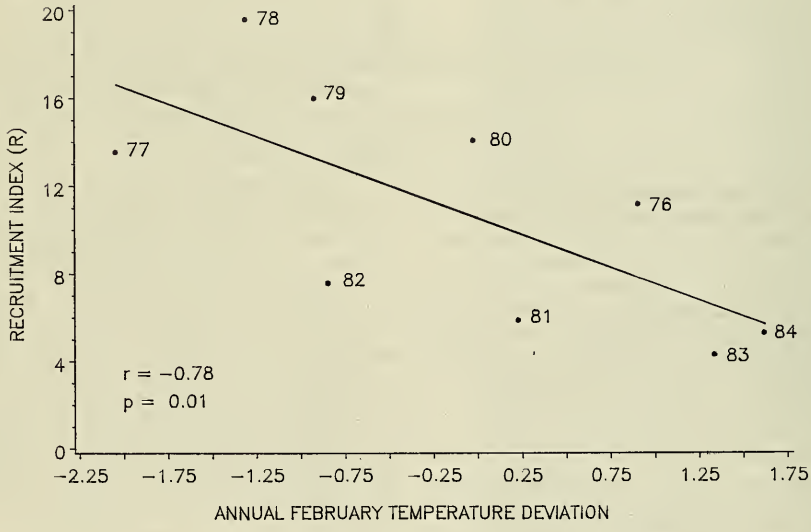


Fig. 14. Relationship between annual age 3 recruitment index and corresponding February water temperature deviations from a long-term mean.

Shepherd et al. (1984) and Sissenwine (1984) cautioned in the use of data exploration exercises not based on plausible *a priori* hypotheses and pointed out the risks of finding spurious correlations from empirical studies. Fundamentally different empirical models may also be indistinguishable because they account for virtually the same proportion of variability in recruitment. However, even without clear evidence for causal relationships, circumstantial evidence may be adequate and empirical models can serve as the basis for the creation and testing of future hypotheses (Garrod 1982; Shepherd et al. 1984). Definitive explanations do not yet exist to explain why February water temperatures were correlated with winter flounder recruitment. This period encompasses much of the period of egg deposition, incubation, and hatching. Most likely, temperature is a surrogate for a complex set of physical and biological interactions. Winter flounder egg incubation time and hatching success (Scott 1929; Williams 1975; Rogers 1976) and larval growth (Laurence 1975; NUSCO 1987) were related to temperature. Temperature may also be correlated with other ecological factors affecting reproductive success. Most importantly, it probably affects the timing of the match of larval production with that of their prey and predators, thereby strongly influencing the success of a year-class (Cushing 1973).

Accordingly, the difference between each annual February mean water temperature from the 11-year mean of 2.4°C was used as a third variable in the Ricker stock and recruitment model. The result was an improved fit ($R^2 = 0.78$) to the observed data (Fig. 15). Estimated values of recruitment using the three-parameter model followed the predictions relatively closely (Fig. 16). February water temperatures helped to explain the previously mentioned difference between 1978 and 1984; the former year was among the coldest and the latter the warmest of the series. The 1978 year-class was also reported by Gibson (1987) to be exceptionally large in Rhode Island. This was not unexpected nor were the high correlations found among abundance indices for the Niantic River stock and others in the region. Climatic

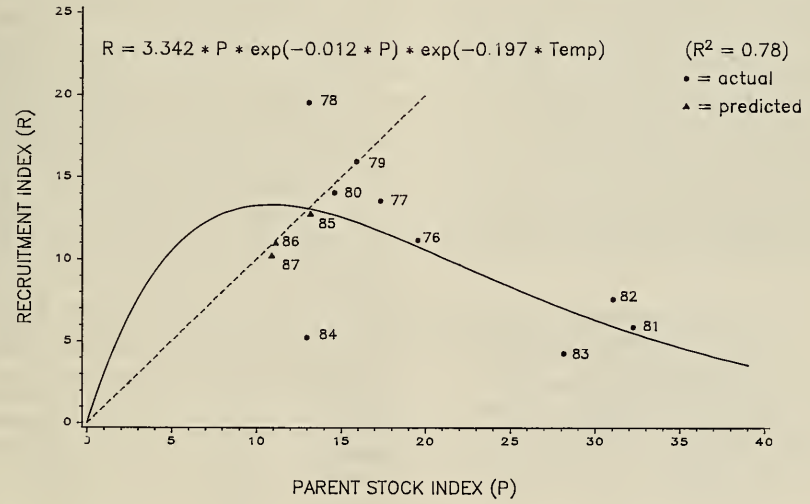


Fig. 15. Temperature-dependent stock-recruitment model (three-parameter) for Niantic River winter flounder.

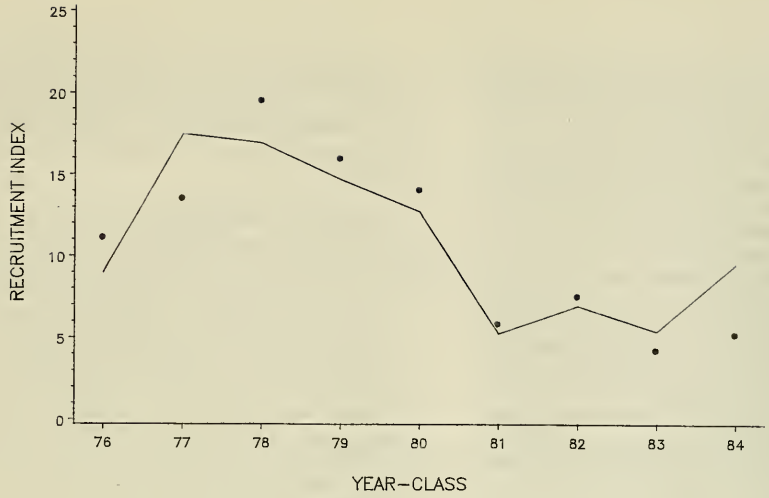


Fig. 16. Niantic River winter flounder recruitment indices for the 1976-84 year-classes predicted by the three-parameter model (line) compared to values actually observed (circles).

influences on recruitment appear to be phenomena fairly pervasive and occurring over large areas and for a number of different species (Cushing 1973; Sissenwine 1984). The use of the temperature parameter φ in the model as well as the relatively large estimate of the α parameter implies that environmental and other density-independent processes are important factors in winter flounder reproduction as noted by Roff (1981) for several flatfishes. However, the density-dependent parameter (β) of the model must operate to adjust year-class strength, as the relatively small variations in recruitment suggest some stabilization mechanism.

Given the relatively cold winters that occurred during the late 1970s (Fig. 17) along with moderate parental stock abundance, good to exceptional year-classes resulted in large parent stock sizes from 1981 through 1983. The relatively abundant adults coupled with mostly above-average temperatures through the present have resulted in the below-average recruitment and decreased winter flounder abundance presently seen. Recent warm winters suggest that a large increase in winter flounder will not occur in the near future. However, when parental stock size and prevailing water temperatures for 1985-87 were used with the stock and recruitment relationship, moderately improved recruitment seems likely during 1988-90 as shown by the three predicted points (Fig. 15). Future values of age 3 CPUE may be compared to those predicted by the three-parameter model to examine its credibility. This would also address a criticism of Sissenwine (1984) in that empirical models often fail to predict post-publication events. However, as the number of data points used for the model was relatively small, the addition of others in forthcoming years will likely change parameter estimates to an unknown degree and model reliability will likely improve. Finally, increasing knowledge of the reproductive process and early life history of the winter flounder may enable the formulation and testing of plausible hypotheses concerning stock and recruitment mechanisms and density-dependent mortality.

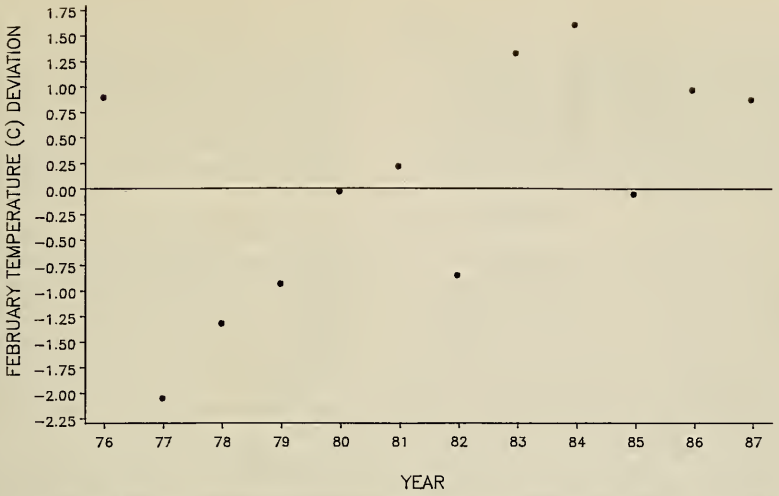


Fig. 17. Annual February water temperature deviations from the long-term mean from 1976 through 1987 as determined from MNPS operating records.

Larval studies

Abundance and distribution

Larval winter flounder abundance in 1986 and 1987 was examined in the Niantic River (stations A, B, and C combined) and Bay (stations EN and NB combined) using estimated abundance curves from the Gompertz function (Fig. 18). In the river, larvae were much more abundant in 1987 and in both years maximum densities occurred during late February through mid-March. The highest densities in the bay occurred later in April and the difference in abundance in the bay between the 2 years was not as great as it was in the river. This suggested that greater larval mortality may have occurred in 1987 compared to 1986 and that the mortality occurred early in the season while a majority of the larvae were in the river. A comparison of the abundances in 1986 and 1987 to 1983-85 was based on the α parameter from the Gompertz function, which was used as an index of abundance (Table 11). This parameter is actually an estimate of the area under the abundance curves presented above (Fig. 18). The Gompertz function fitted the cumulative abundance data well with R^2 values exceeding 0.98.

TABLE 11. Larval winter flounder abundances and 95% confidence intervals for the Niantic River and Bay as estimated by the α parameter from the Gompertz function.

Year	Niantic River		Niantic Bay	
1983	1814	(1748-1879)	2911	(2873-2950)
1984	5077	(4940-5215)	1823	(1742-1904)
1985	11715	(11558-11871)	1604	(1548-1660)
1986	1677	(1629-1726)	881	(843-920)
1987	5066	(4870-5262)	1279	(1234-1324)

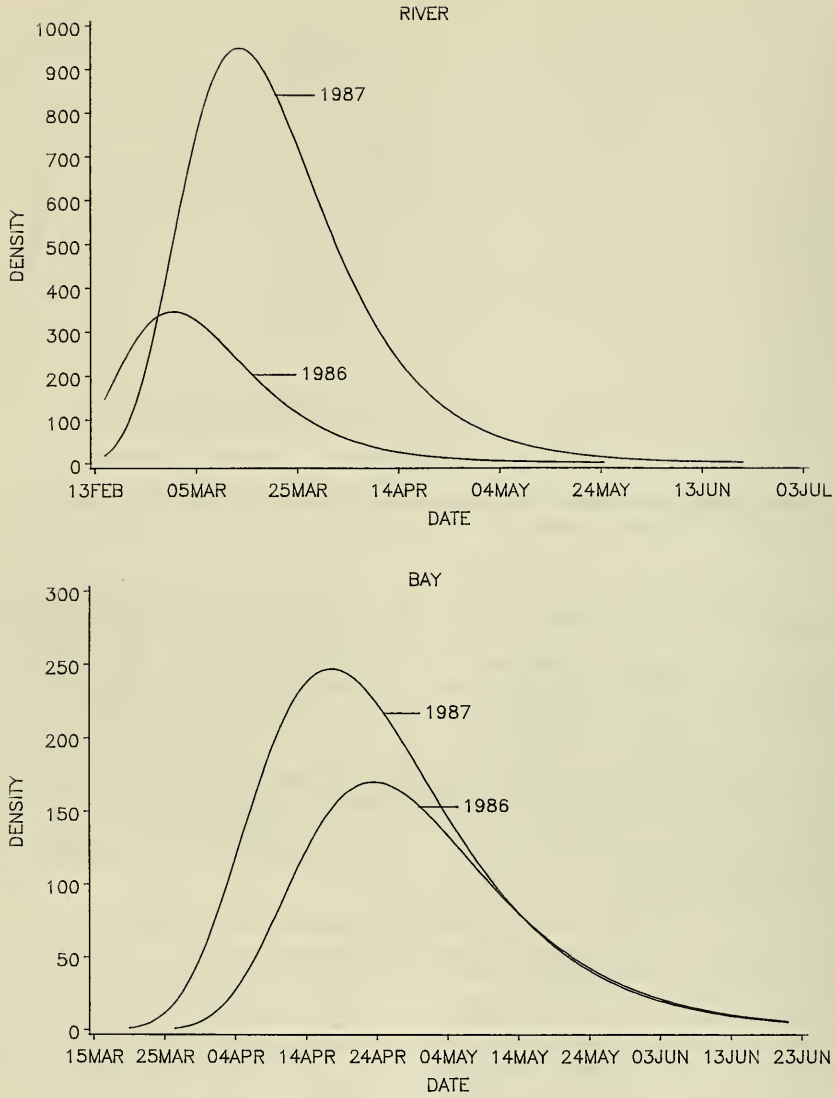


Fig. 18. Estimated abundance curves (number per 500 m^3) for larval winter flounder at Niantic River and Bay stations for 1986 and 1987.

Larvae were least numerous in 1986 in both the river and bay. The abundance of larvae in the river was similar in 1984 and 1987. Abundance in the river did not necessarily reflect that in the bay, as larvae were most abundant in the river in 1985, but were only found in moderate numbers in the bay that year.

Comparisons of annual spatial abundance of the first four developmental stages were based on the cumulative weekly geometric means; because few Stage 5 larvae were collected, their abundance and distribution was not examined. At the three river stations (A, B, and C), Stage 1 abundance was lowest in 1986, except for 1983 (Fig. 19). The low abundance in 1983 was attributed, in part, to undersampling due to net extrusion (NUSCO 1987) and this was rectified in 1984 when a smaller 202-μm mesh net was used during the early portion of the larval season. Comparison among years at each river station showed a similar pattern in Stage 1 abundance with 1985 the highest, followed by 1987, 1984, 1986, and 1983. Stage 1 larvae were rarely collected in Niantic Bay at station EN and NB, suggesting that little, if any, spawning occurred in the bay. By developmental Stage 2, larvae were more prevalent in the bay, but a majority were still collected in the river. Stage 2 larvae were least abundant in 1986 at all five stations. The order of annual abundance for Stage 2 larvae among years was generally the same for the three river stations, although 1987 dropped from second to fourth in rank. Most Stage 3 larvae were collected in the lower portion of the Niantic River (station C) and in the the bay (stations EN and NB) with very few present in the upper river (station A). Abundance in 1986 was lowest at all stations, but the magnitude of the difference compared to other years was not as great. The pattern and relative abundance of Stage 3 larvae were similar among years at stations EN and NB. Stage 4 larvae were collected primarily in the lower river and in Niantic Bay. The low abundance of other developmental stages in 1986 was not as apparent at Stage 4 of development. The large decline in abundance from Stage 3 to 4 in each year was probably related to less effective sampling for older larvae. By Stage 4 of development, the left eye has migrated to or past the mid-line and the larvae have become mostly demersal and thus were less susceptible to either the bongo sampler or entrainment at MNPS. The similar abundance of all stages at EN and NB, which are approximately 1 km apart, suggested a relatively uniform distribution of larvae throughout Niantic Bay.

The decline in abundance of larvae as they passed through developmental stages was quite variable between years. For example, Stage 1 and 2 larvae were the most abundant in 1985 at all river stations compared to other years, but Stage 3 larvae were among the least abundant, implying that high mortality occurred during Stage 2 of development. In 1984, however, Stage 1 and 2 abundances were moderate and Stage 3 abundance at station C was the highest of the 5-year period, indicating low mortality during Stage 2. Although this variability could be attributed to the imprecision of plankton sampling, the consistency in the relative ranking of years for Stages 1 and 2 at the three river stations and for Stage 3 at the two bay stations suggested that the precision in quantifying larval abundance was good. Also, the similar abundance of Stage 3 larvae at EN and NB each year implied that both techniques provided comparable results, even though the sampling methods at these stations were different. Variability in the relative ranking of abundance from stage to stage among years was reported by Bannister et al. (1974) for egg and larval stages of the plaice, which they felt was consistent with density-dependent mortality. The lack of a pattern in the decline in abundance among years indicated that the processes that regulated larval winter flounder abundance were complex and operated at different levels from year to year.

A comparison of the temporal occurrence of developmental stages was based on the date of peak abundance in the river and bay, which was estimated from the inflection point of the Gompertz function (Table 12). Because Stage 1 larvae were rarely collected in the bay, the dates of peak abundance could not be estimated for this area. The dates of peak abundance of each

Fig. 19. Cumulative density by developmental stage for larval winter flounder at each station from 1983 through 1987.

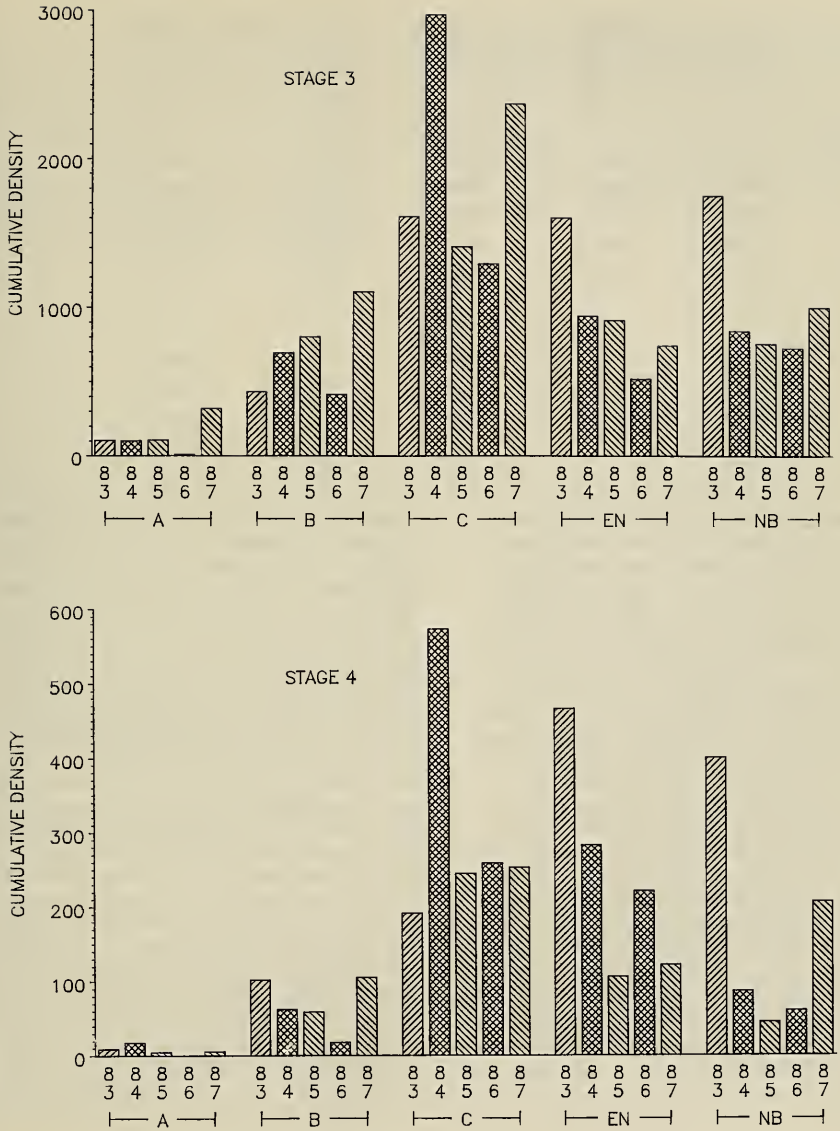

STAGE 3
CUMULATIVE DENSITY
3000
2000
1000
0
STAGE 4
CUMULATIVE DENSITY
600
500
400
300
200
100
0
8 3 8 4 8 5 8 6 8 7
A
B
C
EN
NB

Fig. 19. Cont'd.

TABLE 12. Estimated dates of peak abundance of larval winter flounder for each developmental stage in the Niantic River and Bay.

Year	Stage 1	Stage 2	Stage 3	Stage 4
		Niantic River		
1983	Mar 5	Mar 15	Apr 18	May 1
1984	Mar 7	Mar 9	Apr 26	May 19
1985	Mar 12	Mar 16	Apr 28	May 15
1986	Feb 26	Mar 7	Apr 23	May 12
1987	Mar 10	Mar 15	Apr 22	May 9
		Niantic Bay		
1983	-	Apr 7	Apr 22	May 7
1984	-	Apr 9	May 2	May 23
1985	-	Mar 31	Apr 26	May 15
1986	-	Apr 7	Apr 28	May 9
1987	-	Apr 5	Apr 24	May 16

developmental stage in the river and bay were fairly consistent during the 5-year period. Stage 1 larvae generally peaked in early March, or in 1986, during late February. This corresponded with the observations on spawning adult females during the adult surveys. Based on water temperatures of 2 to 3°C during the latter portion of February and egg incubation times reported by Buckley (1982), peak spawning probably occurred in mid-February. In the river, Stage 2 larvae peaked in mid-March, but the dates of peak abundance in the bay were 15 to 31 days later. As noted in NUSCO (1987), the lag in peak abundance of Stage 2 larvae in the bay may have been related to flushing rate, because the average retention time of a passive particle in the Niantic River was reported as 25 to 27 days (Moore and Marshall 1967; Kollmeyer 1972). In each year the peak abundance dates for Stage 3 and 4 larvae were very similar in both the river and bay. This similarity, along with the lag in the date of peak abundance for Stage 2 larvae, suggested that the larvae were flushed from the river primarily during that developmental stage.

Predation could have affected larval abundance and there are numerous accounts that jellyfish are predators of fish larvae. Several species of hydromedusae and the scyphomedusa *Aurelia aurita* were found to prey upon herring larvae (Arai and Hay 1982; Moller 1984). Laboratory studies with cod, plaice, and herring showed that the capture success by *A. aurelia* increased with medusal size (Bailey and Batty 1984). Evidence of a causal predator-prey relationship on larvae of two European flatfishes (*Pleuronectes platessa* and *Platichthys flesus*) by *A. aurita* and the ctenophore *Pleurobrachia pileus* was reported by van der Veer (1985). Pearcy (1962) stated that *Sarsia tubulosa* medusae were important predators of larval winter flounder in the Mystic River, CT, and had greatest impact on younger, less motile individuals. Crawford and Carey (1985) reported large numbers of the moon jelly (*A. aurata*) in Point Judith Pond, RI and felt that they were a significant predator of larval winter flounder. The medusae of the jellyfish *Cyanea* sp. has been suspected of being an important predator of larval winter flounder in the upper portion of the Niantic River (NUSCO 1987). This hypothesized predation was based on data collected at station A

during 1983-85 as measured volumes of jellyfish were lowest in 1985 when Stage 2 larval abundance was the highest. In addition, laboratory studies had shown that a larva which contacted a tentacle was stunned and ultimately died, even if not consumed. Jellyfish abundance in 1986 was similar to 1983 and that in 1987 was similar to 1985, but the numbers of Stage 2 larvae at station A in 1986 and 1987 were both low compared to 1985 (Fig. 20). However, this does not discount the potential of jellyfish predation. Abundance of Stage 2 larvae in 1987 was low at all stations and this possibly obscured observations on the effects of predation. Although the predator-prey relationship of jellyfish on winter flounder larvae in the Niantic River was not as clear as once thought (NUSCO 1987), the fewer older larvae (Stages 3 and 4) in the upper portion of the river may have been related to jellyfish predation.

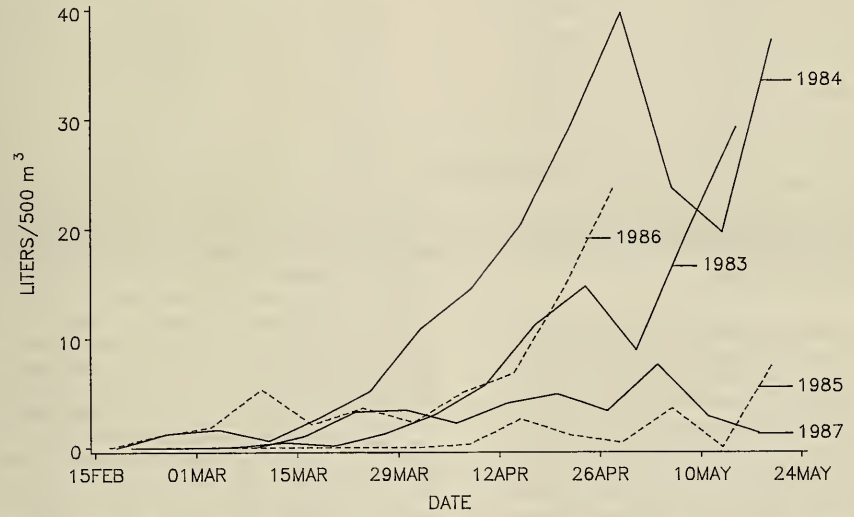


Fig. 20. Weekly mean volume (liters per 500 m^3) of *Cyanea* sp. medusae collected at station A in the Niantic River from 1983 through 1987.

Entrainment of larvae at MNPS

The number of winter flounder larvae entrained by MNPS was related to larval densities in Niantic Bay and plant operations. Generally, larvae were entrained from late February through June with most entrainment occurring from mid-April through May. The median larval densities from entrainment collections in 1986 and 1987 were some of the lowest since 1976, but the estimated numbers entrained were among the highest due to the start-up of Unit 3 (Table 13). Although Unit 3 did not start producing commercial power until April 23, 1986, condenser cooling-water pumps in operation varied throughout the occurrence of winter flounder larvae in Niantic Bay during 1986. The percentages of each developmental stage respectively entrained in 1986 and 1987 were similar, with Stage 1 representing 2% in both years; Stage 2, 21% and 29%, Stage 3,

TABLE 13. Annual median densities (number per 500 m^3) of winter flounder larvae in entrainment samples during their season of occurrence and total entrainment estimates with approximate 95% confidence intervals for MNPS in 1976 through 1987.

Year	Median	95% CI	Total Estimate ($x10^6$)	95% CI ($x10^6$)
1976	158.0	114-188	94.8	68-113
1977	64.1	53-87	29.3	24-40
1978	86.6	65-106	57.8	43-70
1979	90.3	70-108	36.7	28-44
1980	201.5	164-235	40.6	114-164
1981	139.2	99-183	47.4	34-62
1982	183.5	148-215	126.6	102-148
1983	244.4	158-315	171.7	111-221
1984	185.5	108-226	90.4	52-110
1985	107.1	79-153	66.0	49-94
1986	94.0	73-120	109.4	85-139
1987	88.9	65-109	126.2	93-154

61% and 62%; and Stage 4, 15% and 8%. The proportion of each developmental stage entrained was similar to previous years with Stage 3 predominating (NUSCO 1987).

The 12 years of entrainment sampling provided a long time-series of data that were examined to determine if seasonal water temperatures affected the timing of peak abundance. Seasonal water temperatures were expressed as the deviation from the 12-year mean. The date of peak abundance was highly correlated to water temperatures during March and April (Fig. 21). The warmer the water temperature, the earlier the peak that occurred, which suggested that the rate of larval development increased with increasing temperature. This was in agreement with the findings of Laurence (1975), who found that winter flounder larvae metamorphosed 31 days earlier at 8°C than at 5°C.

The date of peak abundance, estimated from the inflection point of the Gompertz function, was calculated using the β and κ parameters. The κ parameter was correlated to February water temperatures and as temperatures decreased, the parameter declined (Fig. 22). The κ parmeter determined the shape of the abundance curve with steeply peaked curves for larger κ values. To demonstrate how the this parameter affects abundance distribution, abundance curves were simulated with two different κ values, but with the same α and β values (Fig. 23). For winter flounder, February water temperatures would primarily affect spawning and egg incubation, because peak larval abundance occurs later (Table 12). A significant relationship was found between the annual κ value and the age 3 recruitment indices that were used for the analysis of stock and recruitment (Fig. 24). It appeared that the shape of the larval abundance curve, as determined by February water temperature, was important in determining year-class strength, although the actual causal mechanisms were not known.

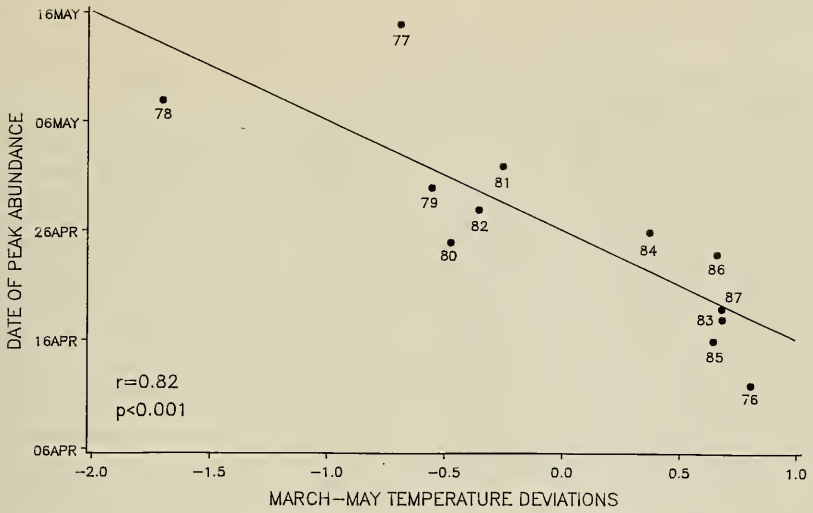


Fig. 21. The relationship between the estimated annual date of peak abundance of entrained winter flounder larvae and the annual temperature deviation during March through May.

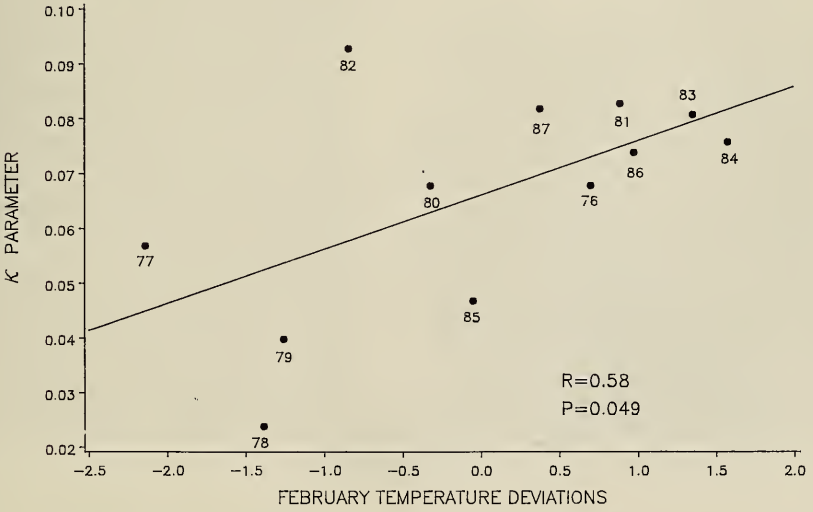


Fig. 22. The relationship between the κ parameter of the Gompertz function for entrained winter flounder larvae and the annual February temperature deviations with the fitted regression line.

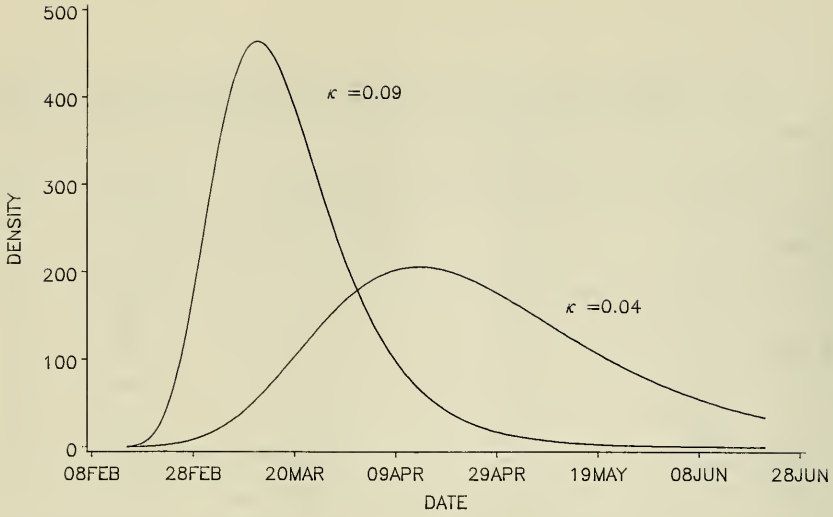


Fig. 23. A simulation illustrating the effect of different Gompertz κ parameter values with constant α and β values on the shape of larval abundance curves.

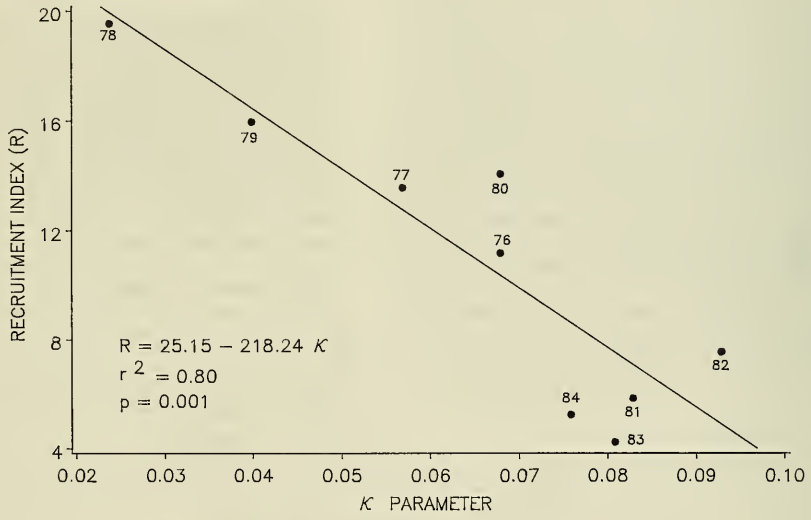


Fig. 24. The relationship between the κ parameter of the Gompertz function for entrained winter flounder larvae and the age 3 recruitment index lagged 3 years with the fitted regression line.

Growth

Examination of the length-frequency distribution of larvae collected in 1986-87 showed a separation between the first three developmental stages by predominant 0.5-mm size-classes (Fig. 25). Stage 1 larvae were primarily in the 2.5 to 3.5-mm size-classes (95%), Stage 2 were 3.0 to 4.5 mm (86%), Stage 3 were 4.5 to 7.5 mm (86%), and Stage 4 were 6.5 to 8.5 mm (92%). These predominant size-classes for each developmental stage were consistent with previous findings (NUSCO 1987), indicating that development and length were closely related. This allowed for the approximation of developmental stage from length-frequency data.

A comparison was made of the length-frequency distribution between Niantic River and Bay in 1986-87 (Fig. 26). The pattern found was similar to that of the spatial distribution of developmental stages for the same year (Fig. 19). Smaller size-classes predominated in the river, with over 60% of them 3.5 mm or smaller. In contrast, over 50% of the larvae in the bay were 5.0 mm and larger. These patterns were similar to those found in previous years (NUSCO 1987) and was further evidence that a majority of the larvae hatched in the Niantic River and then gradually flushed into the bay. Based on the large decline in the river from the 3.0- to the 4.0-mm size-class, it is likely that this was the size range where most of the mortality occurred. Larvae in these size-classes would have been yolk-sac larvae (Stage 1) and first-feeding Stage 2 larvae. In a bioenergetic study on winter flounder larvae, Laurence (1977) found that they had a low energy conversion efficiency at first feeding compared to later development, and that this stage of development was probably a "critical period" for mortality. The "critical period" concept was first hypothesized by Hjort (1926) and discussed by May (1974) for marine fishes. In many cases, the strength of a year-class was thought to have been determined by the availability of sufficient food after yolk-sac absorption was completed. However, the occurrence of a "critical period" depended upon a number of environmental and species-specific factors (May 1974). The small increase in frequency of larvae from the 5.0- to 7.0-mm size-classes in the river may have been caused by the net import of these larger larvae into the river due to the behavioral retention mechanisms discussed in NUSCO (1987). Previous sampling during ebb and flood tides at the mouth of the river showed a net loss of larvae smaller than 5 mm from the river, but a net import of larger larvae. This was attributed to vertical migration by larger larvae in relation to tidal stage as a retention mechanism to remain in the river. These larvae apparently swam up from the bottom during flood tides and remained near bottom during ebb tides. The decline in frequency after the 7.0-mm size-class probably was due to undersampling as larvae metamorphosed and became less susceptible to capture with a plankton net.

The effects of temperature on larval growth was examined in the laboratory in 1986 under four temperature regimes. Larvae were reared from hatches on March 6 (treatments I and II) and April 1 (treatments III and IV). Linear regression was used to estimate growth rates and reasonable fits were obtained with r^2 values of 0.85 and higher (Fig. 27). The rate of yolk absorption was similar in all treatments, but growth rates differed (Table 14). Temperature comparisons between treatments were based on the first 40 days from hatching. Growth rates were significantly lower in lowest and highest temperature regimes compared to the intermediate treatments. This limited laboratory study suggested that larval winter flounder have an optimum temperature range for growth, and as the temperature decreased or increased from the optimum, growth rates decreased.

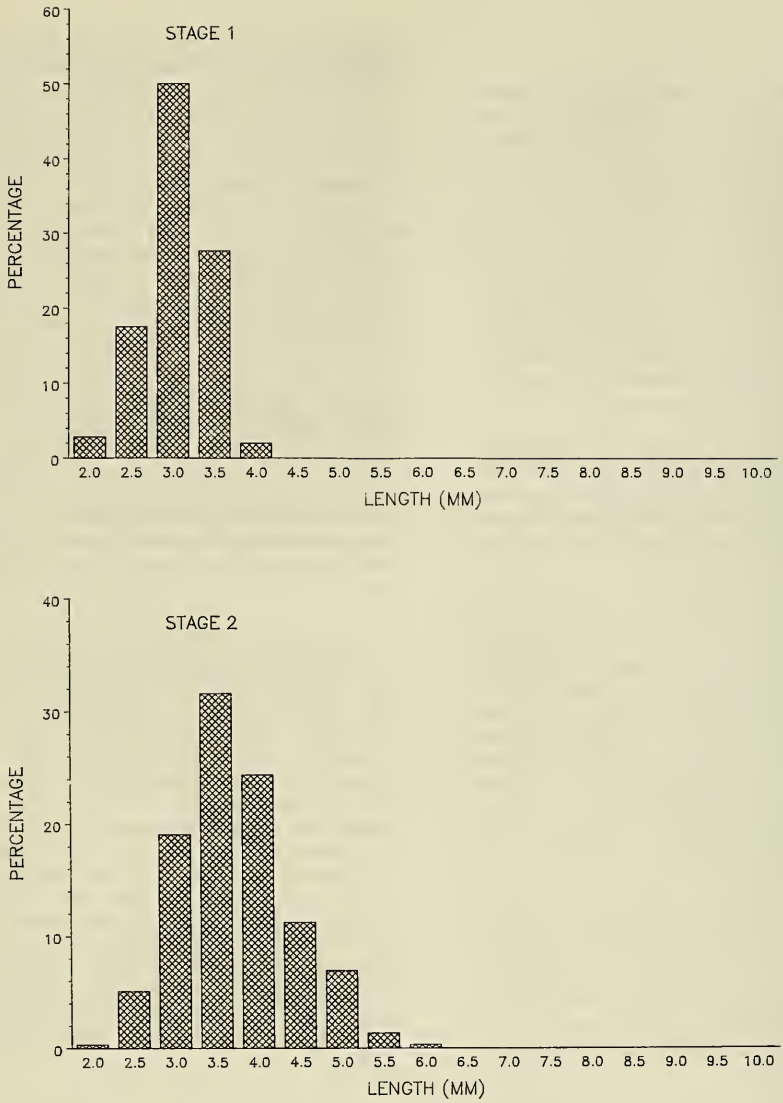
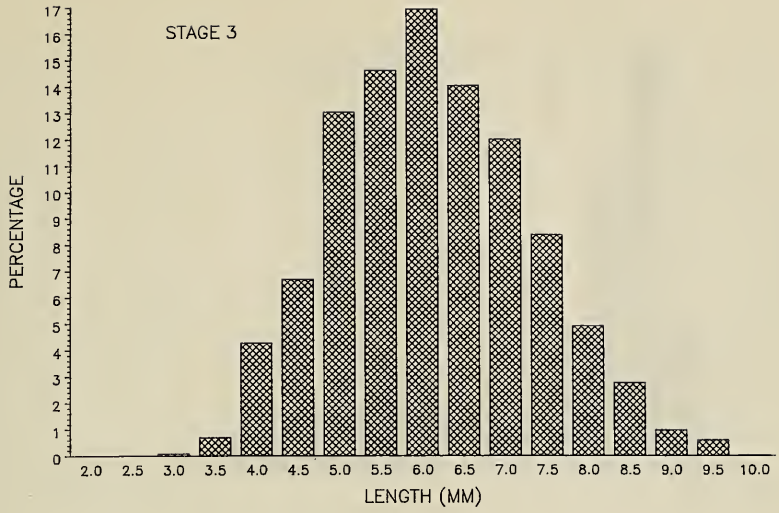


Fig. 25. Length-frequency distribution of larval winter flounder by developmental stage for all stations in the river and bay combined for 1986 and 1987.


STAGE 3
PERCENTAGE
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5 10.0
LENGTH (MM)

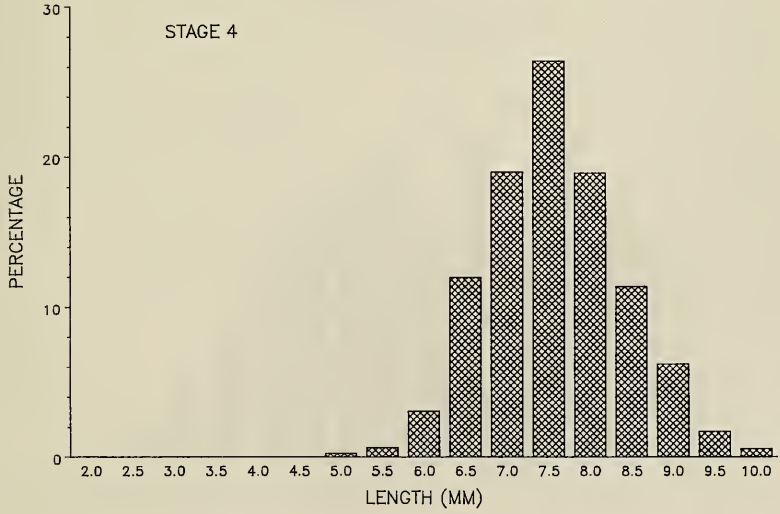

STAGE 4
PERCENTAGE
0
10
20
30
2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5 10.0
LENGTH (MM)

Fig. 25. Cont'd.

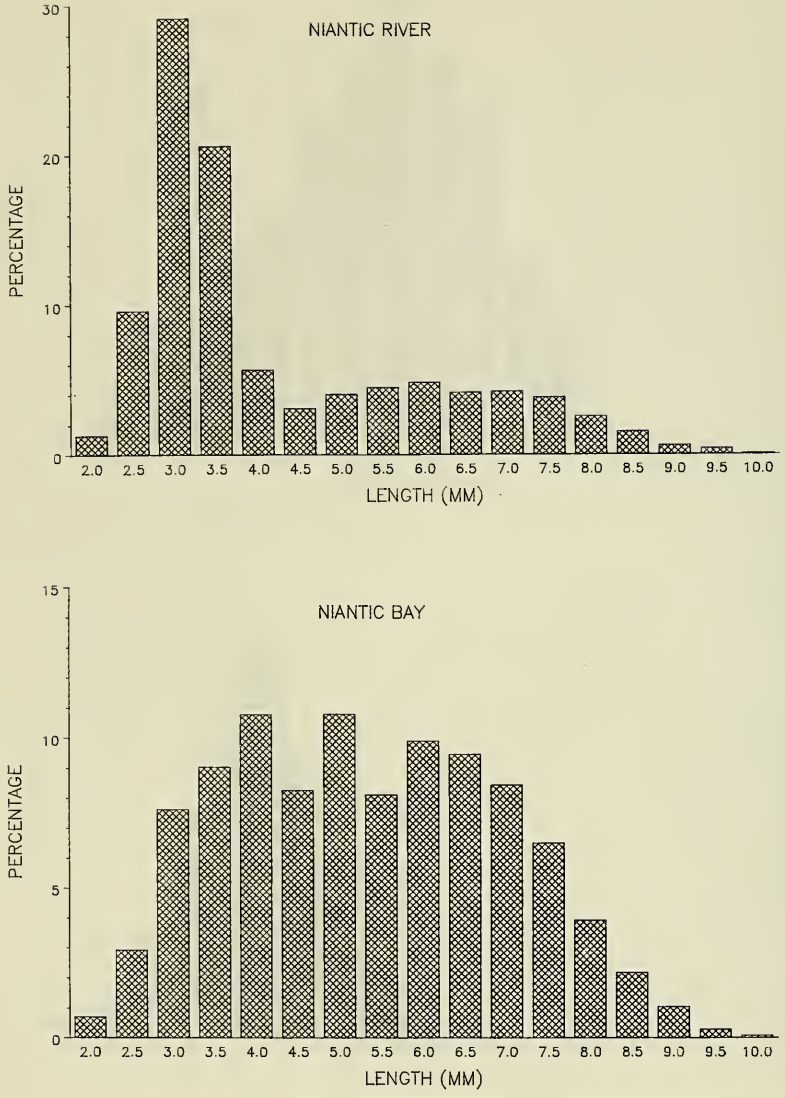


Fig. 26. Length-frequency distribution of larval winter flounder for all stations combined in the Niantic River and Bay for 1986 and 1987.

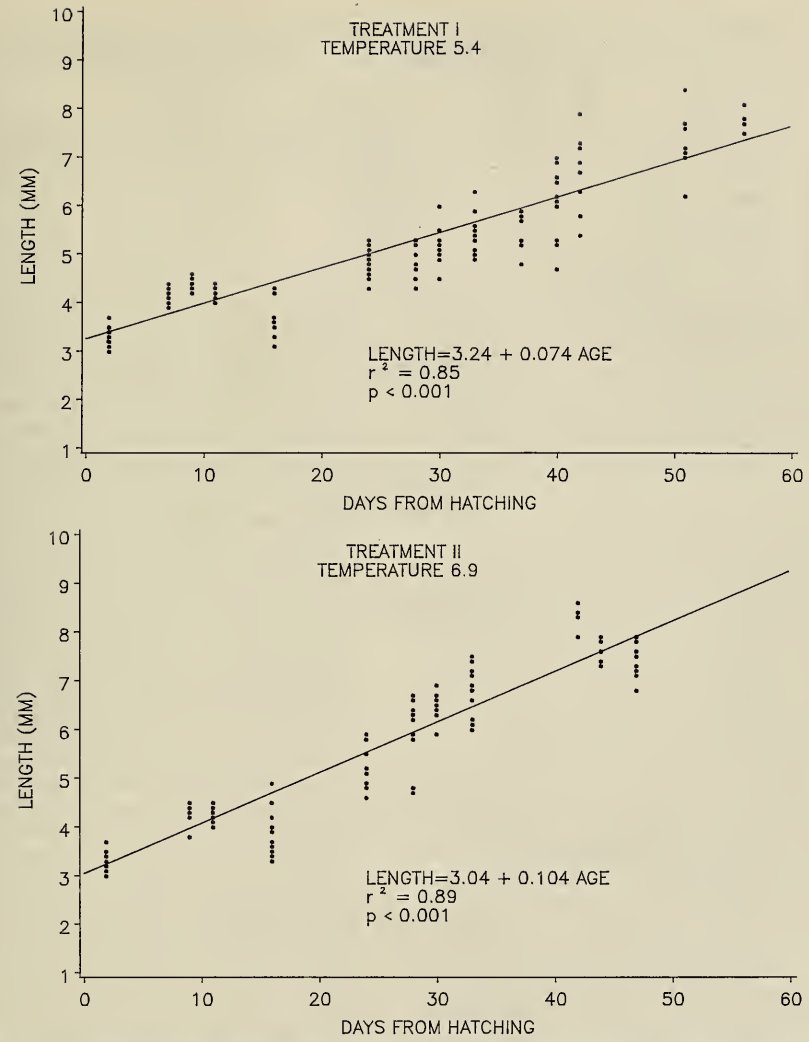
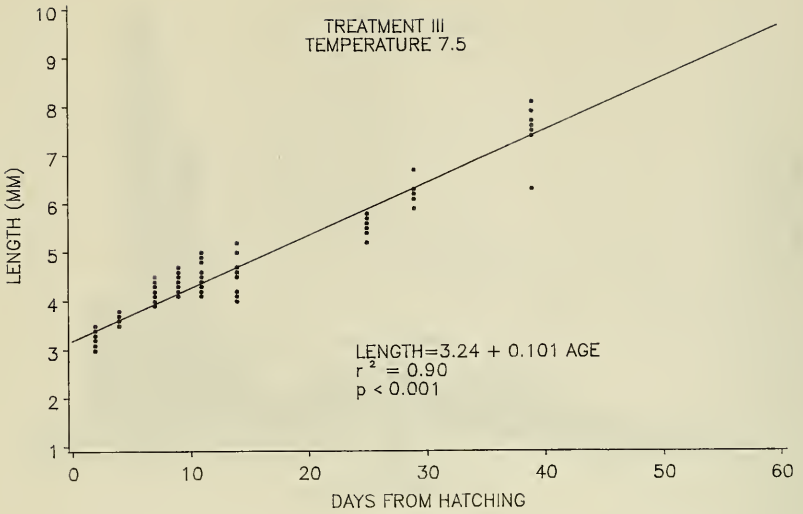


Fig. 27. Plot of individual length measurements of laboratory-reared winter flounder larvae at four temperature regimes and fitted regression line used to estimate growth rates.


TREATMENT III
TEMPERATURE 7.5
LENGTH (MM)
LENGTH=3.24 + 0.101 AGE
r² = 0.90
p < 0.001
DAYS FROM HATCHING

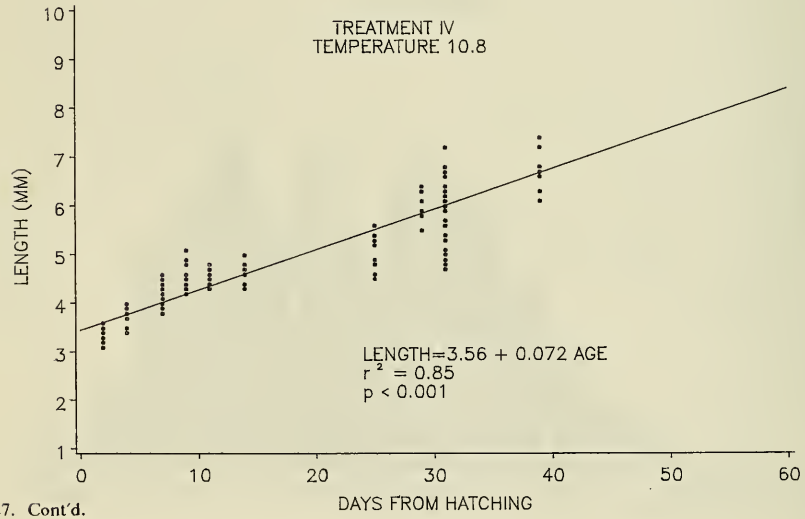

TREATMENT IV
TEMPERATURE 10.8
LENGTH (MM)
LENGTH=3.56 + 0.072 AGE
r² = 0.85
p < 0.001
DAYS FROM HATCHING

Fig. 27. Cont'd.

TABLE 14. Larval winter flounder yolk absorption time and growth rate from hatching through 40 days at four temperature regimes in a laboratory rearing study.

Treatment	Mean temperature (40-d)	Temperature range	Yolk absorption (d)	Growth rate (mm/day)
I	5.4	3.3-7.5	10	0.074 ± 0.0048
II	6.9	4.4-8.4	8	0.104 ± 0.0064
III	7.5	4.8-10.5	10	0.101 ± 0.0057
IV	10.8	7.3-14.7	8	0.072 ± 0.0034

Other laboratory growth studies on winter flounder larvae (Laurence 1975, 1977; Buckley 1980, 1982) were not directly comparable to our results because the published growth rates were not expressed in length. Buckley (1982) reported enhanced growth, measured as protein weight, at a constant temperature of 10°C compared to 5 and 7°C, whereas a decrease in growth was found in our study at a mean temperature of 10.8°C compared to 6.9 and 7.5°C. This inconsistency could have been related to insufficient food in our study, as Laurence (1975) found increased metabolic demands with increasing temperature. During our study, we attempted to maintain excess food levels, but no quantitative sampling of prey densities was conducted. The results of treatments I, II, and III agreed with the laboratory results of Laurence (1975), with growth rate increasing as temperatures increased from 2 to 5 to 8°C. Growth was expressed as a daily percent increase in weight from the time of first feeding, or as daily specific growth rates (SGR). In an attempt to make a comparison, the estimated length at 40 days from hatching was converted to weight by a length-weight relationship and the estimated weight at first feeding was the mean weight (11.9 µg) at first feeding of the three treatments reported by Laurence (1975). Estimated SGR for treatments I, II, III and IV were 10.3, 13.6, 12.7, and 11.9% per day, respectively. These estimates were higher than those reported by Laurence for 2, 5, and 8°C of 2.6, 5.8 and 10% per day, respectively. The laboratory conditions of other studies on larval winter flounder growth differed from ours because constant temperatures were maintained throughout development. The gradual increase in temperature during development in our study was meant to more closely mimic actual field conditions during larval development. Whether the difference in growth rates expressed as SGR was related to the increasing temperatures during the study or an artifact of converting length to weight was not known.

Mean weekly lengths at station C were used to estimate larval growth rates for comparison with the laboratory-rearing data. This station was used because all developmental stages were collected there in abundance (Fig. 19). Examination of mean weekly lengths for each year since 1983 showed that growth through time had a sigmoid shape (Fig. 28). During the beginning of the larval season, the weekly mean lengths remained fairly constant at about 3 mm, the approximate size at hatching, due to the recruitment of large numbers of newly-hatched larvae. During the latter portion of the season, mean lengths remained constant or declined, probably due to the loss of metamorphosing larvae that were no longer susceptible to capture. To estimate growth rates, a linear regression was fit to those weekly means that showed a consistent increase from week to week during the middle of the larval season (Table 15). The range of annual estimated growth rates were similar to those found in the laboratory at the intermediate temperature regimes (treatments II and III). Mean water temperatures were calculated from data collected by a continuous temperature recorder located at a dock near the mouth of the Niantic River. For 1983 through 1985 these data were available only as weekly means.

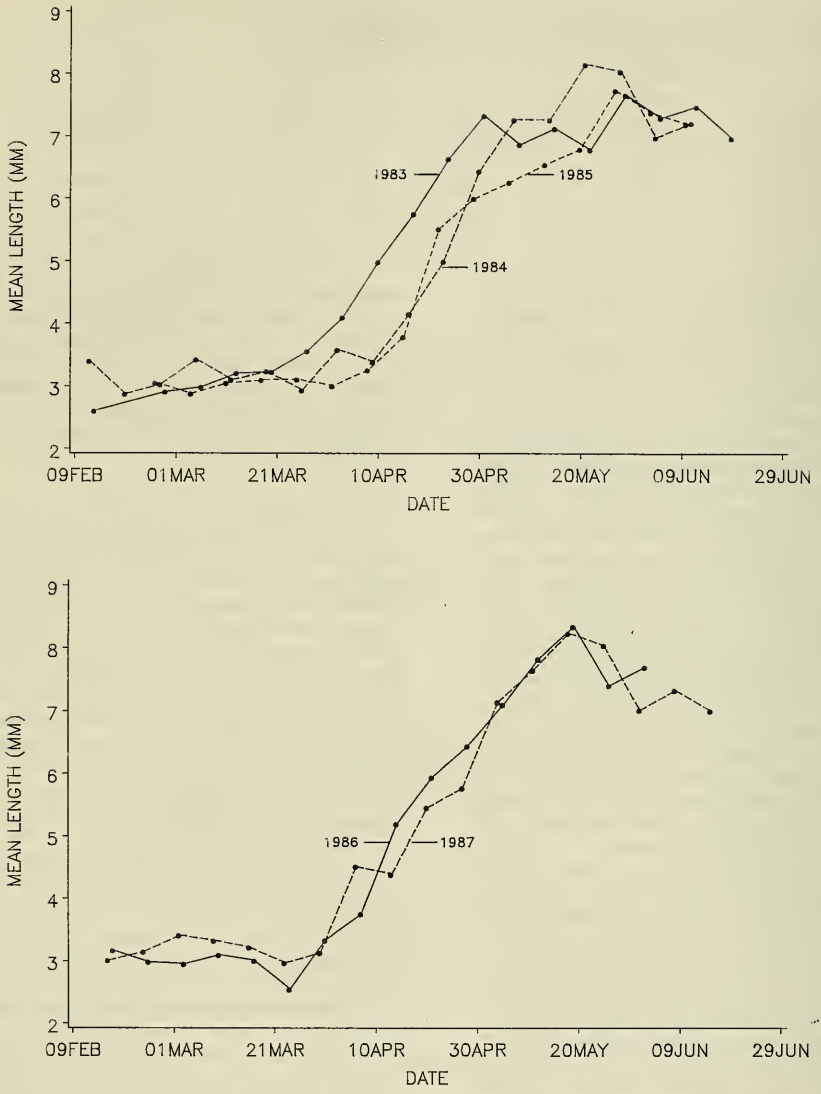


Fig. 28. Weekly mean length of winter flounder larvae at Station C in the Niantic River from 1983 through 1987.

TABLE 15. Estimated larval winter flounder growth rates at station C in the Niantic River based on linear regression, with r^2 values, of weekly mean length and mean water temperature during the first six weeks of each time period.

Year	Time period included[a]	Growth rate mm/day (S.E)	r^2	Mean water temperature[b]
1983	Mar 20-May 1	0.103 (0.005)	0.99	7.9
1984	Mar 25-May 6	0.104 (0.014)	0.92	7.2
1985	Mar 31-May 26	0.085 (0.008)	0.99	9.6
1986	Mar 23-May 4	0.113 (0.007)	0.98	7.6
1987	Mar 22-May 10	0. 98 (0.008)	0.96	7.4

[a]Time period of weekly mean lengths used in estimating growth rate

[b]Mean during a 6-week period starting the week of the of the first weekly mean length used in estimating the growth rate.

The mean water temperature for each year was calculated for a 6-week period starting in the same week that the first mean length was used in the growth rate calculation. Mean water temperatures were similar in all years, except for 1985, which was the highest and also had the lowest growth rate. The slower growth in 1985 could have been further evidence for an optimum temperature for growth and if temperatures were too high, growth rates would have decreased. Also, another possibility was that growth was density-dependent, as Stage 2 larvae in 1985 were the most abundant at station C over the 5-year period (Fig. 19). Laurence (1977), in a laboratory study on larval winter flounder at 8°C, reported a decrease in growth rate as prey densities decreased. With just 5 years of data (4 of them had similar temperatures) and no information on prey densities, it was not possible to discriminate between the effects of temperature and food availability on growth rates.

The densities of larvae collected at EN provided a long time-series and should have been representative of larval abundance in Niantic Bay. Sampling frequency was high with 18 samples per week in 1976-82 and 8 samples per week in 1983-87. Annual growth rates were estimated in a fashion similar to station C above. A linear model adequately described growth using weekly mean lengths (Table 16). In general, growth rates were lower in the bay than at station C. Average daily water temperatures were available from continuous temperature recorders in the MNPS intake and a comparison of mean water temperatures in the lower Niantic River and in the bay during March through May for 1983-1987 showed that temperatures in the bay were consistently lower. During the 5-year period this seasonal difference ranged from 0.4 to 1.5°C. Although this difference was small, a similar difference in mean water temperature in the laboratory of 5.4 to 6.9°C caused significantly different growth rates (Table 14). Mean water temperatures were determined for a 40-day period starting at the beginning of the week when the first weekly mean length was used in estimating the growth rate. A positive relationship was found between growth rate and water temperature, which was described by a two-term polynomial equation (Fig. 29). The increased growth rate with temperature would have accounted for the earlier dates of peak abundance seen at higher temperatures and illustrated on Figure 21.

In conclusion, food availability and water temperature appeared to have been the two most important factors controlling larval growth (Buckley 1982). Houde pointed out that surprisingly small changes in growth could have large effects on subsequent recruitment in fishes. Slight declines in growth rate caused by less than optimum food, unfavorable temperatures, disease, or pollution can lead to longer developmental times

TABLE 16. Estimated larval winter flounder growth rates in Niantic Bay from data collect at station EN based on linear regression, with r^2 values, of weekly mean length and mean water temperature during the first 40 days of the time period.

Year	Time period included[a]	Growth rate mm/day (S.E)	r^2	Mean water temperature[b]
1976	Mar 21-May 2	0.091 (0.010)	0.95	7.0
1977	Apr 3-Jun 5	0.072 (0.006)	0.95	6.7
1978	Mar 26-Jun 11	0.057 (0.005)	0.92	4.8
1979	Mar 25-Jun 10	0.062 (0.006)	0.91	5.9
1980	Mar 23-Jun 8	0.061 (0.003)	0.97	5.9
1981	Apr 5-May 31	0.078 (0.011)	0.88	7.3
1982	Mar 28-May 30	0.063 (0.005)	0.95	5.8
1983	Mar 6-May 22	0.055 (0.002)	0.99	5.2
1984	Mar 25-May 13	0.066 (0.005)	0.96	6.4
1985	Mar 17-Jun 2	0.058 (0.005)	0.94	6.0
1986	Mar 30-May 11	0.095 (0.005)	0.99	7.6
1987	Mar 22-May 17	0.075 (0.005)	0.97	7.0

[a]Time period of the weekly mean lengths used to estimate growth rate

[b]Mean during a 40-day period starting at the beginning of the week that the first weekly mean length used in estimating the growth rate.

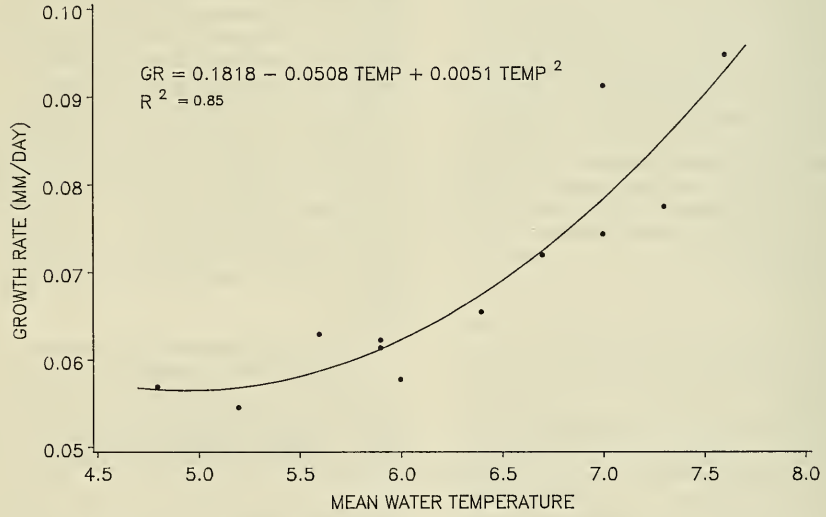


Fig. 29. Relationship between mean water temperature and estimated growth rates of entrained winter flounder larvae from 1976 through 1987 with the fitted quadratic polynomial regression line.

by stage during which high rates of mortality operate. Although Laurence (1975) demonstrated that the metabolic demands of larval winter flounder increased at higher temperatures, the growth rate also increased if sufficient food resources were available. However, other laboratory studies (Laurence 1977; Buckley 1980) have shown that larval winter flounder growth rates are dependent on prey availability.

In Niantic Bay, water temperature appeared to have strongly affected growth, but in the Niantic River it was less clear what factor was most important in controlling growth.

Mortality

Mortality rates of larval winter flounder were estimated from data collected from three Niantic River stations. Data from 1983 were excluded as smaller larvae were undersampled because of net extrusion (NUSCO 1987). The 3.0-mm and smaller size-classes were used as an abundance index of newly-hatched larvae because this was the approximate length at hatching and the 3.0-mm size-class was collected most frequently (Fig. 26). The rapid decline in the frequency of larvae in the 3.5- and 4.0-mm size-classes was attributed to both natural mortality and tidal flushing from the river. Hess et al. (1975) estimated the loss of larvae from the entire river as 4% per tidal cycle and also determined that the loss from the lower portion of the river was about 28% per tidal cycle. Therefore, the daily abundance estimates of larvae in the 3.0-mm and smaller size-classes at station C (located in the lower portion of the river) were increased by a factor of 1.93 to compensate for the 28% decline per tidal cycle with two cycles per day. Tidal studies conducted in the Niantic River suggested that older larvae (Stages 3 and 4) utilized vertical migration in response to tidal flow to enter the river and those within the river used a similar behavior to remain there (NUSCO 1987). The increasing frequency of larvae in the 6.0- to 7.0-mm size classes was at least partially attributed to this behavior, so the number of larvae in the 7.0-mm size class was used as an abundance index of larvae nearing the end of Stage 3 of development.

For the mortality calculations, abundance indices for newly-hatched larvae, after adjustment for tidal flushing, and for larvae in the 7.0-mm size class were determined by summing the mean weekly abundance (three stations combined) during each larval season. Survival rate from hatching through Stage 3 was estimated as the ratio of the abundance index of the larger larvae to that of the smaller larvae. Total larval mortality through Stage 3 for 1984-87 ranged from 84.6% to 96.9%, which represented a mean instantaneous rate (Z) of 2.58 (Table 17). These larval mortality rates are only preliminary estimates until additional aging information is available and new simulation studies are conducted to better estimate tidal flushing rates. Previous attempts to age larvae by examining otoliths with a light microscope were not successful (NUSCO 1987), but an improved technique developed at University of Rhode Island (Dr. A. Durbin, pers. comm.) may allow the use of otoliths to age winter flounder larvae.

Post-larval young-of-the-year studies

Abundance

Beginning in 1983, a 1-m beam trawl was used weekly in the Niantic River to collect post-larval young-of-the-year winter flounder from late May through the end of September (NUSCO 1987). Kuipers (1975) reported that a similarly-designed 2-m beam trawl with at least one tickler chain (the 1-m trawl has two) was nearly 100% efficient in catching plaice smaller than 70 mm. Kuipers (1975) and Poxton et al. (1982) noted that efficiency of a beam trawl decreased for larger young in fall and winter due to changes in behavior,

TABLE 17. Estimated larval winter flounder total mortality from hatching to 7 mm.

	Abundance Index			
Year	Newly hatched	7.0-mm size-class	Mortality(%)	Z
1984	7,005	635	90.94	2.401
1985	13,733	424	96.91	3.478
1986	2,459	379	84.59	1.870
1987	6,488	469	92.77	2.627
				mean = 2.594

increased ability to avoid the net, increased swim speed, lowered availability, and perhaps increased alertness with age. Therefore, sampling was discontinued in the Niantic River at the end of summer as water temperatures began to decline and before young winter flounder left the shallows.

In most years, abundance of young winter flounder at stations LR and WA peaked in early June, most likely when larval recruitment began to be offset by mortality (Fig. 30). In 1986 at WA, an initial peak in early June was followed by a normal decrease (Fig. 31). However, abundance increased to another peak in late July before again declining. Weekly catches were also more variable at WA in 1986 than in 1987, but the converse was true at LR. The reason for the variability in densities may have been due to small-scale differences in young winter flounder distribution. At WA, field notes indicated that positions of tows varied more by replicate and from week to week in 1986 than during 1987. Greater effort was made to maintain a more uniform tow path at WA in 1987. In earlier years, the area available for tows at LR was well-defined by surrounding beds of eelgrass (*Zostera marina*). By contrast, eelgrass was nearly absent there in 1987 and this led to increasing lateral variability in tow position. At times, differences among replicates were striking and the movement of a few meters from the rock rip-rap along the highway often meant large differences in the number of young caught as well as in the amounts of algae, detritus, and other organisms. The increase in density seen from August to September in 1987 at LR was due, in part, to a slight shift in tow path closer to the shoreline. Some differences in catch may also have been attributed to varying net efficiency because of bottom type or algae and detritus loads.

Comparison of moving averages of weekly abundance among years showed that initial densities of young were considerably higher in 1987 than in previous years and at LR generally remained so throughout the season (Fig. 32). Abundance in 1986 was also greater than in 1983-85 and peaked later during the season. By August, relatively high abundance at WA in 1987 declined to levels seen previously, with densities in 1986 appearing to have been only marginally greater.

Growth

Growth of young was illustrated by changes in weekly mean length (Fig. 33). After a relatively rapid increase from May through July, further growth occurred at a slower rate throughout the remainder of summer with little or no increase in weekly means during September. Growth was less variable than densities were and weekly means had relatively small 95% confidence intervals. Unlike previous years, when mean lengths at LR significantly exceeded that at WA by 20 mm or more in summer (NUSCO 1987), smaller differences in growth were noted in 1986 and 1987, with no significant differences found between stations during the latter year.

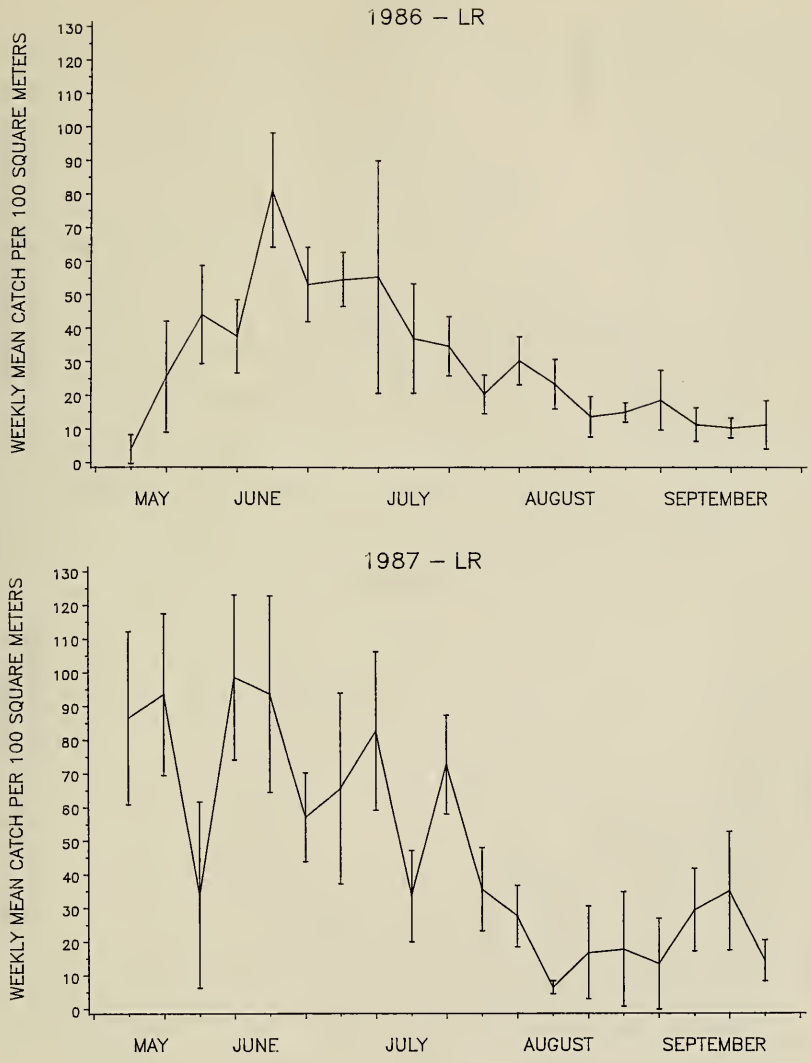


Fig. 30. Weekly mean CPUE (±2 standard errors) of young winter flounder taken at station LR in the Niantic River during 1986 and 1987.

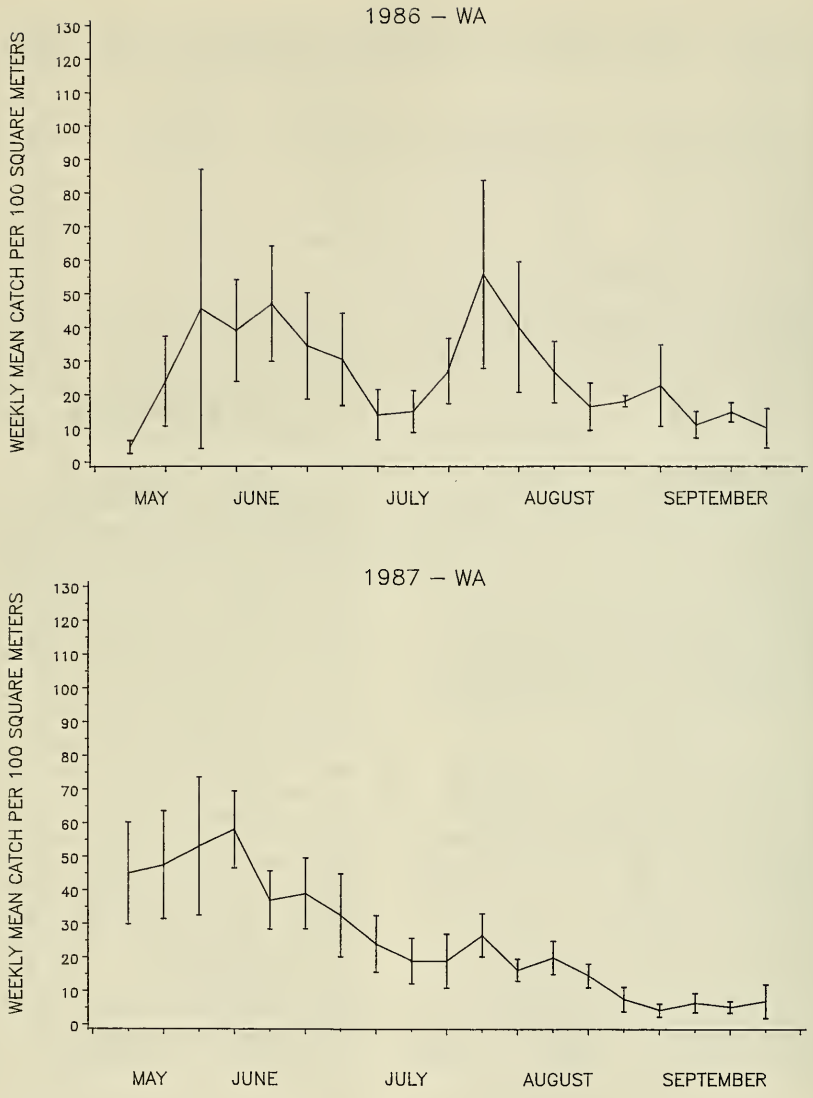


Fig. 31. Weekly mean CPUE (±2 standard errors) of young winter flounder taken at station WA in the Niantic River during 1986 and 1987.

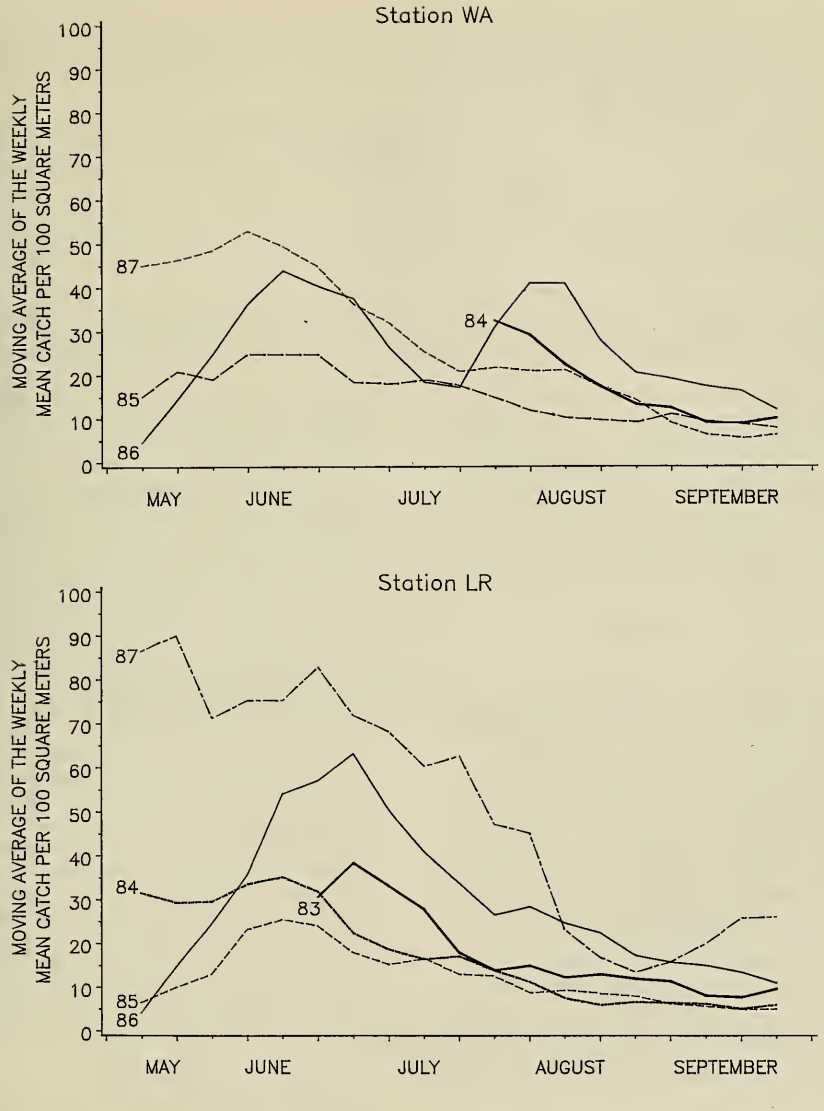


Fig. 32. Moving average of weekly mean CPUE of young winter flounder taken in the Niantic River from 1983 through 1987.

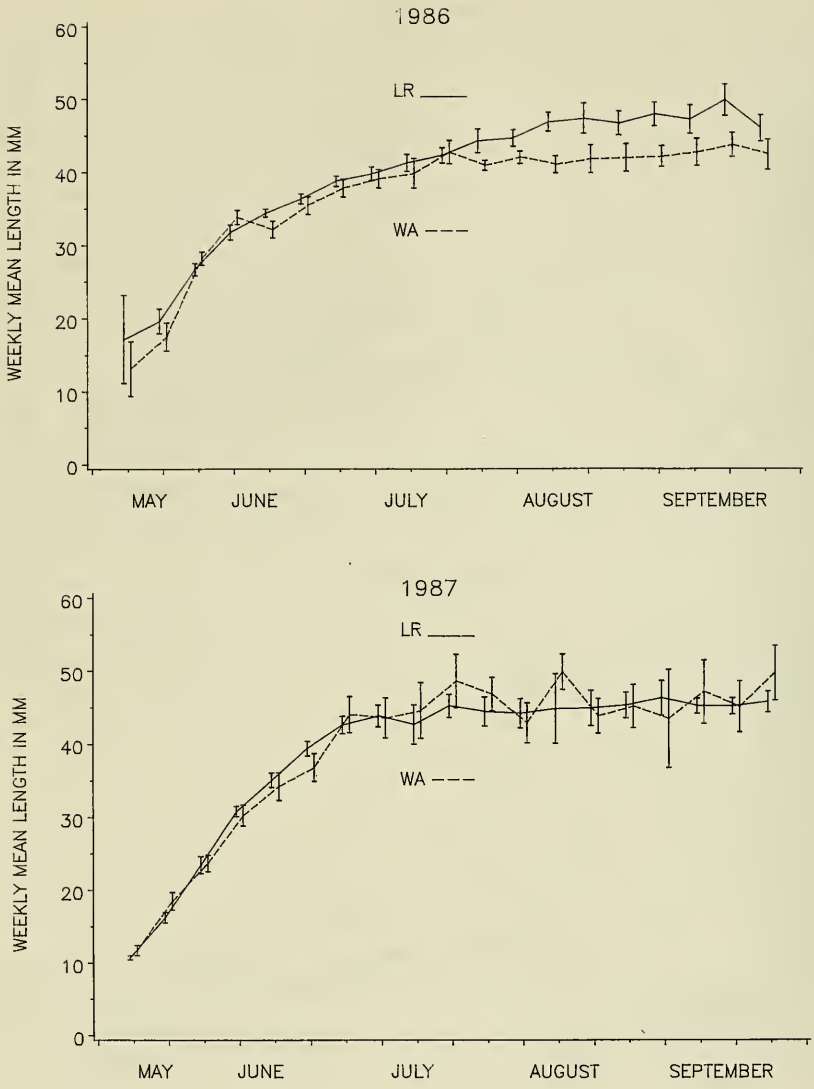


Fig. 33. Weekly mean length (± 2 standard errors) of young winter flounder taken in the Niantic River during 1986 and 1987.

TABLE 18. Monthly survival rate estimates for young winter flounder taken at two stations in the lower Niantic River from 1983 through 1987 as determined by a catch curve.

Year	Monthly survival rate (S) at station: LR	WA
1983	0.552	--
1984	0.564	--
1985	0.569	0.661
1986	0.553	0.335 (early); 0.440 (late)
1987	0.597	0.511
Average annual survival rate[a]:	0.567	0.507

[a] Determined from the average of the corresponding estimates of instantaneous mortality rate Z.

Weekly mean lengths at LR during 1983-85 were similar by year until about late June; means were 6 to 8 mm greater thereafter during 1983 (Fig. 34). Growth in 1986 and 1987 was alike, but means were less than in previous years. Smaller differences were seen in growth among years at WA. Average size of young appeared to be greater in July during 1987, but if 95% confidence intervals were shown, no significant differences would have been found in August and September. The reasons for these differences among years are not known. Water temperatures appeared to be comparable; seasonal 19-week means ranged from 18.9°C in 1987 to 19.5°C in 1985. Life history data such as food preferences and rates of feeding were not available, but both were considered important factors in the growth of young plaice (Steele and Edwards 1970; Poxton et al. 1983). Apparent annual changes in growth may also have been caused by differential movement of larger young away from the station, which also would have increased the apparent mortality rate. However, few young were taken during the summer at trawl monitoring program stations. Thus, neither large-scale movements offstation nor differential movements by size seemed to have occurred, at least into areas sampled by trawl.

A tentative explanation for the differences observed among years is density-dependent growth, especially at LR. Densities there in 1986 and 1987 were greater than during 1983-85. Benthic production and food availability at the stations may have been a limiting factor for growth. Density-dependent growth in juvenile fish has been regularly observed (Cushing and Harris 1973; Ware 1980; Poxton et al. 1983; van der Veer 1986). This may be demonstrated conclusively in forthcoming years, if greater densities are observed with concurrent slower rates of growth.

Mortality

To determine instantaneous mortality (Z) and weekly and monthly survival rates (S), catch curves were constructed using annual abundance data from LR for 1983-87 and WA for 1985-87. This method assumed that young comprised a single-age cohort which was followed from week to week during the sampling season. Catch curves and estimates of Z and S for 1983-85 were given in NUSCO (1987). The catch curves for LR data from 1986 and 1987 had relatively good fits with r^2 of 0.70 and 0.89, respectively (Fig. 35). Remarkably similar values of Z were obtained over all years, resulting in monthly survival estimates of 0.552 to 0.597 (Table 18). Estimates of survival were more variable at WA (Fig. 36). The fit to the data in 1985 (NUSCO 1987) was not as good ($r^2 = 0.56$) and monthly survival rate was estimated as 0.661.

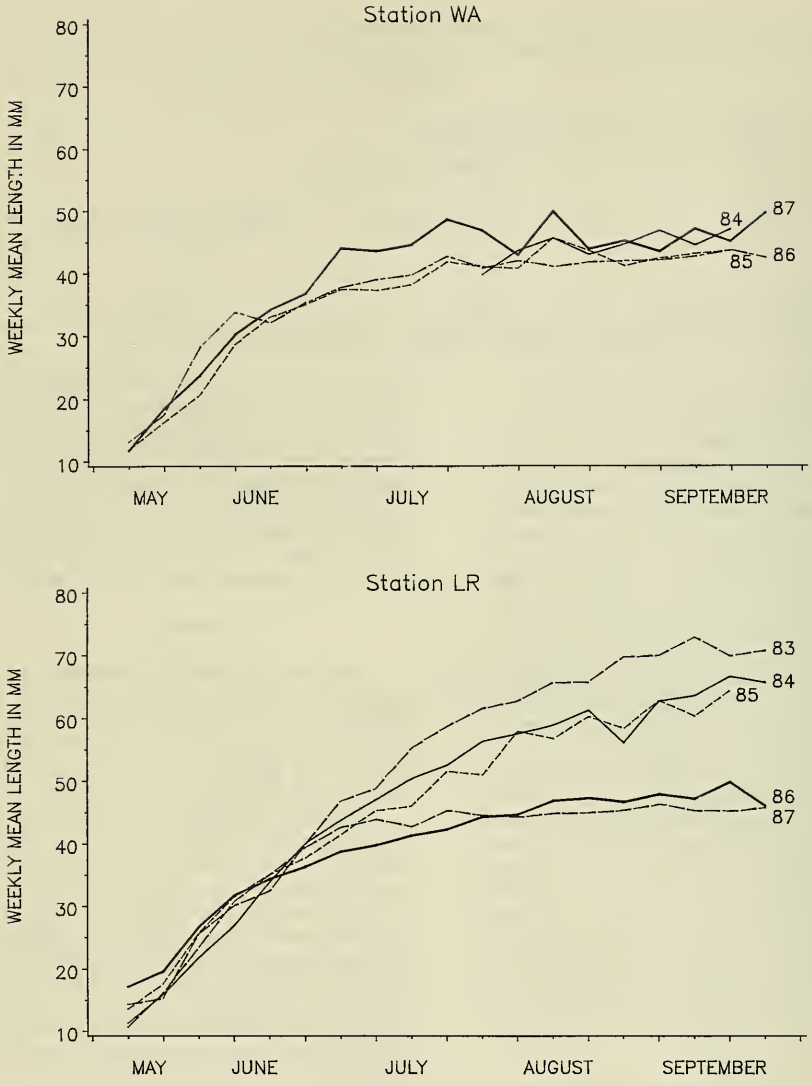


Fig. 34. Comparison of weekly mean length of young winter flounder taken at stations LR and WA in the Niantic River from 1983 through 1987.

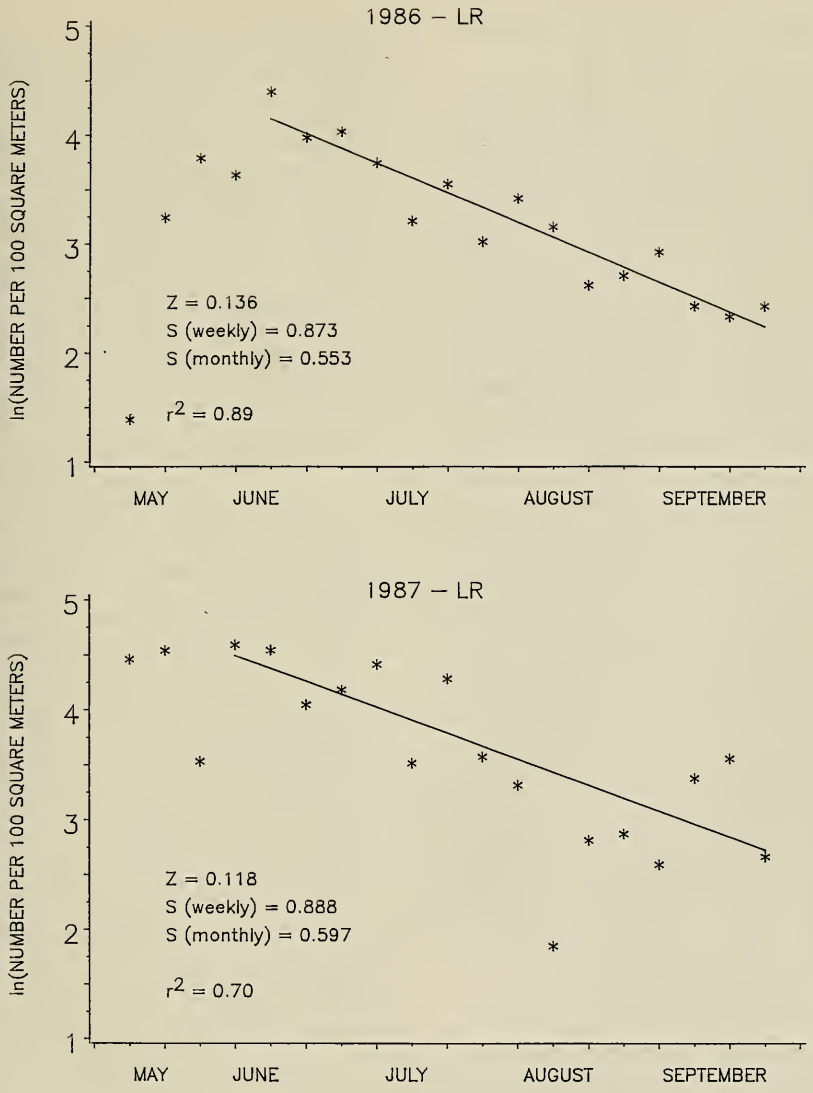


Fig. 35. Mortality determined by catch curve for young winter flounder taken at station LR in the Niantic River during 1986 and 1987.

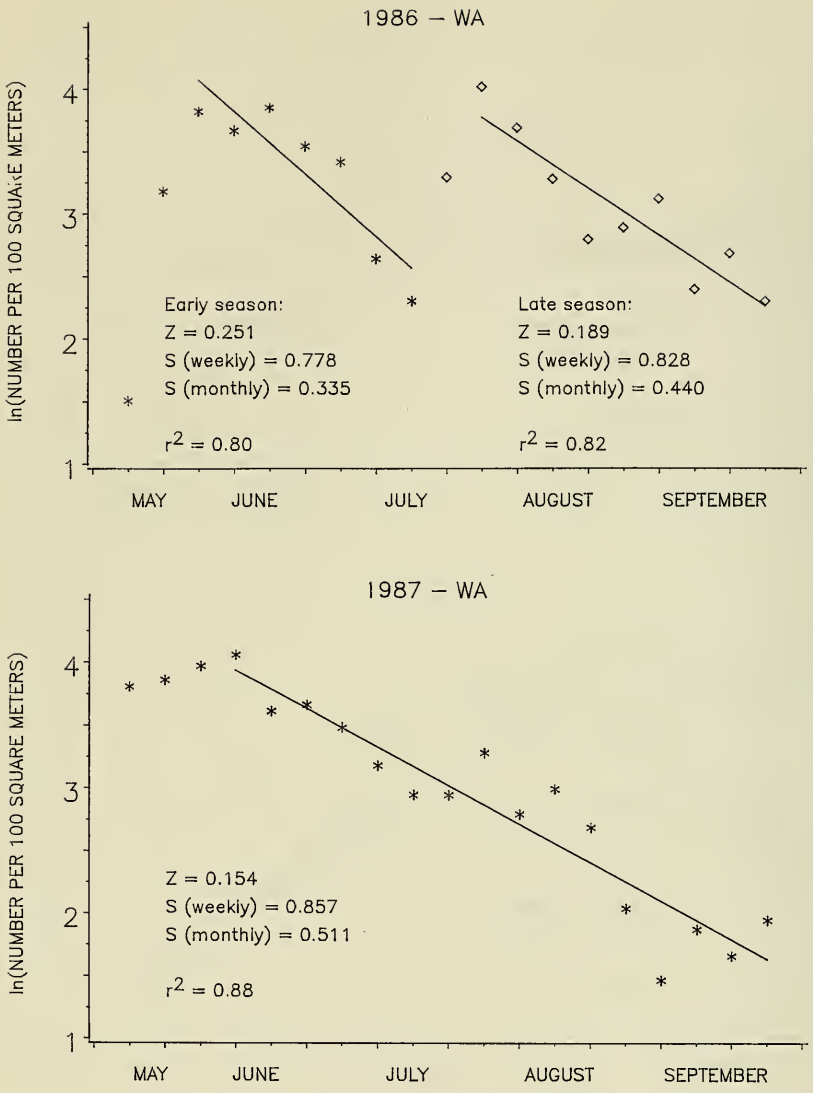


Fig. 36. Mortality determined by catch curve for young winter flounder taken at station WA in the Niantic River during 1986 and 1987.

Because of the previously mentioned increase in abundance during mid-summer of 1986, two catch curves were used, resulting in early (0.335) and late (0.440) seasonal estimates of monthly survival rate. Although the above partitioning of the data resulted in good fits, this apparent sampling problem made the survival estimates unreliable. The 1987 monthly survival rate of 0.511 appeared to be based on more accurate density estimates. Overall, survival may not have been as high at WA as LR, although additional sampling will be necessary to confirm this. The monthly survival rates in the Niantic River were less than the value of 0.69 reported by Pearcy (1962) for the Mystic River estuary, which is the only published estimate for young winter flounder. Most monthly survival rate estimates for young plaice in British coastal embayments also were about 50% per month (Lockwood 1980; Poxton et al. 1982; Poxton and Nasir 1985).

Density-dependent processes in the first year of life following the larval stage are believed to occur in a number of species and can greatly affect subsequent recruitment to adult stocks (Bannister et al. 1974; Cushing 1974; Sissenwine 1984). Density-dependent mortality was not apparent for post-larval Niantic River winter flounder, at least over the range of abundances seen to date. In fact, the highest survival rate estimated was in 1987, when densities were greatest. Density-dependent mortality was reported for young plaice by Bannister et al. (1974), Lockwood (1980), and van der Veer (1986). However, examination of their findings indicated that greatest rates of mortality occurred only when extremely large year-classes of plaice were produced (three to more than five times larger than the average). The numbers of juvenile winter flounder in the Niantic River since 1983 were probably not extremely large or small enough to have produced density-dependent mortality (should it exist), although densities were apparently different enough to have affected rates of growth.

Impingement of winter flounder at MNPS

Annual estimates of the number of winter flounder impinged on the traveling screens of MNPS have been made since 1972-73 (NUSCO 1987). Since 1976, the winter flounder has been the second-most abundant fish impinged at MNPS, making up 5.9% of the total. About two-thirds of the impingement occurred during the winter with relatively little in summer. Fish return sluiceways have been in place at Unit 1 since December 1983 (NUSCO 1986b, 1987) and at Unit 3 since it commenced commercial operation (NUSCO 1988c). These sluiceways have considerably reduced the impact of impingement as the winter flounder is very hardy and had good (> 85%) survival following return to Long Island Sound. The estimated impingement of winter flounder at Unit 2 was 1,212 for October 1985 through September 1986, 547 during 1986-87, and 77 from October through mid-December 1987. The 1985-86 estimate was less than 50% of the next smallest annual estimate. As in most previous years, about two-thirds of the fish impinged in 1985-87 were less than 20 cm in length. The numbers taken at Unit 2 during the past few years have been small, due to varying plant operations; declining winter flounder abundance; and possibly the construction and operation of Unit 3, which may have altered fish availability and movements near the Unit 2 intake. The latter effect on fish impingement is discussed in the Fish Ecology section of this report. Although impingement is no longer routinely monitored at MNPS, a requirement exists for reporting significantly large (> 300 specimens per day) impingement events, should they occur (NUSCO 1988a).

Impact assessment

Approaches to impact assessment

Considerable effort has been expended during the past 15 years evaluating the impact of fish mortality resulting from the operation of power plants in the United States (Van Winkle 1977; MacCall et al. 1983). For adult fish subject to

impingement the assessment of impact is straightforward and consists of the direct enumeration of fish losses. However, for eggs and larvae subject to entrainment, measurement of primary loss is less direct and assessment of the resulting impact at the population level (as adult fish) is much more difficult. This type of assessment involves two basic tasks: the estimation of organisms entrained as a fraction of the annual production; and the measurement of any resulting population changes. The first task involves sampling at the plant discharge and often the use of hydrodynamics models to predict the spatial distribution of fish eggs and larvae in the vicinity of the plant; and the second requires measuring the size of the adult population in either absolute or relative terms. Because fish populations are complex dynamic entities strongly influenced by the physical environment, the determination of their size and spatial distribution is not easy. It has long been known (Cushing 1977) that marine fish stocks undergo very large fluctuations in abundance, both annual and long-term, primarily induced by climatic and hydrographic factors. This natural and erratic variability creates serious problems for measuring anything but the largest changes. In addition, when knowledge of the range and frequency of long-term fluctuations is lacking, short-term monitoring data may show a misleading and alarming population decline if observations started at the begining of a downturn. This rules out the use of short-term empirical assessment methods because they address impact on a single cohort or year-class in the sense of Goodyear's (1978) adult-equivalent method. An additional problem inherent of the latter method and of most fishery stock-assessment methods is that they assume equilibrium population conditions, which implies a regularity in nature that is contrary to all evidence. All these problems point to the need for parsimonious impact assessment approaches leading to the creation of a substantial data base on which to build a comprehensive fishery assessment model capable of predicting long-term effects at the population level. Preferably, this model should incorporate key biological processes governing recruitment, the effect of environmental factors known to affect year-class strength, and it should not require that the population be at equilibrium.

In assessing the possible impact of MNPS operation on the local winter flounder, NU has recognized the importance of larval losses on the long-term stability of the adult population. The problems of estimating the fraction of larvae entrained and of measuring the resulting population change were examined taking into account the geographic and hydrographic features of Niantic Bay and the spawning and nursery areas in the Niantic River. Therefore, the approach for impact assessment consisted of a combination of sampling programs and analytical methods leading to the development of a comprehensive simulation model which included hydrodynamics and population dynamics submodels. The sampling programs and methods for estimating population parameters, describing larval behavior, and determining the stock-recruitment relationship have been discussed in previous sections. The simulation model components (larval dispersal and entrainment, and population dynamics submodels) and the probabilistic risk analysis methodology for long-term impact assessments are described below.

Larval dispersal and entrainment model

As mentioned previously, one of the two basic tasks in assessing entrainment impacts is to estimate the fraction of total larval production lost to entrainment. The problem here is that, given the location of the plant intakes relative to the spawning and nursery areas in Niantic River and the prevailing tidal currents in Niantic Bay, the use of the number of entrained larvae as a direct loss to the locally spawning stock is not appropiate for impact assessment at MNPS. An early hydrodynamics model of the area used by Saila (1976) predicted that, if larvae behaved as passive particles, most of those flushed out of the river by tidal action would progress towards Millstone Point and would continue moving in an east-southeast direction until they left the area via the Twotree Island Channel. Saila and his coworkers estimated that only 30% of the organisms entering

the bay remain in the vicinity of Millstone after twenty tidal cycles (i.e., about 10 days). Their model also showed that, although larvae leaving the river were subject to entrainment losses, a large fraction of them would have been flushed from the area by tidal action in the absence of power plant entrainment. Because it seems reasonable to expect lower larval survival in the bay (and even more so in open waters of Long Island Sound) than in the protected nursery areas in Niantic River, absolute entrainment numbers do not represent a fair estimate of additional loss due to the operation of MNPS. In this context, the modeling work carried by Dr. Saila's research team at URI represented a first attempt to estimate the actual larval losses attributed to entrainment at MNPS. Since then, new data on the early life history of winter flounder resulting from our own studies (NUSCO 1987) suggested that vertical movements of older larvae in response to tidal and diel cycles may invalidate some of the assumptions made in the early URI models. In order to address this problem NU has contracted for the development of a new larval dispersal and entrainment model with the Department of Civil Engineering at the Massachusetts Institute of Technology (MIT).

This new MIT model will use the hydrodynamics TEA (tidal circulation) and LEA (advective transport) submodels as a framework for larval dispersal and entrainment simulation. These two model components were recently used to describe the dynamics of the thermal plume at MNPS (Adams and Cosler 1987). Although TEA and LEA are nominally similar to the corresponding models used by Hess et al. (1975) and Saila (1976), there are important differences as well. First, both TEA and LEA use irregular, triangular, grid elements, rather than regular, square, grid elements. The former configuration allows for easy grid refinements in critical regions, such as the Niantic River and the plant intake area. Secondly, both submodels take advantage of newly developed computational methods which provide better accuracy and higher speed for extended and more detailed simulations. In addition, the area covered by TEA and LEA in the previous application mentioned above will be extended to include the northern reaches of the Niantic River and to the south, in Niantic Bay, to include a larger portion of the local area in Long Island Sound.

The larval dispersal component of the MIT model will be able to simulate continuous production of newly hatched larvae that matches the actual length of a typical spawning season, and will track larval ages in days. Larval behavior will be simulated by reducing advection (corresponding to larvae moving to the bottom) as a function of tide phase and time of day and according to larval age. Although four larval stages will be simulated separately, simulation results can be presented in terms of total larval population by integrating over larval stages. The model will be run to simulate various scenarios where each will be of seasonal duration involving a repeating average tide. Among contemplated simulations are comparisons between runs with and without larval "behavior", between runs with and without power plant operation, and between runs employing different distributions of larval hatching in space and time. Drifting of "foreign" larvae into the simulation area through the open boundaries will also be simulated to assess the effect of larval sources other than the Niantic River.

Important inputs required by the hydrodynamic components of the MIT model are the tidal boundary conditions and dispersion coefficients which influence flushing from the rivers and dispersion away from the power plant intakes. The tidal boundary conditions will be established by comparing measured and simulated tidal currents. Larval dispersion coefficients will be validated by comparing measured and simulated larval flushing rates from the Niantic River and by comparing measured and computed intake dye concentrations resulting from instantaneous dye releases in Niantic Bay. Additional inputs related to larval dispersion will be the empirically estimated (NUSCO 1987) vertical distribution of larvae at various tides and times of the day. Daily larval mortality rates, needed to simulate naturally occurring larval concentrations in the river and bay

for given spawning locations and hatching rates, will be supplied by NU. Once MIT has validated its model, the computer code will be installed in our own computer system to run additional simulations as new or better input data become available. The MIT model is expected to be completed before the end of 1988.

Population dynamics model

A problem central to modeling the dynamics of fish populations is the difficulty of finding an adequate formulation for describing the recruitment process. Because egg and larval survival is more dependent on environmental factors than adult fish survival, a prominent feature of recruitment data for many fisheries is the large amount of variability present that cannot be attributed to changes in parental stock size. Despite this well-documented fact, past deterministic population models (Christensen et al. 1977; Saila and Lorda 1977) have included in their formulations recruitment equations whose parameters describe only variation in parental stock and assume populations at equilibrium. By contrast, our modeling approach recognizes that the very great temporal variation in recruitment nullifies the concept of "equilibrium" conditions and this mandates stochastic models that account for this variability. This is important because, for commercially exploited species like the winter flounder, the higher the fishing effort, which reduces the average lifetime of the fish and their reproductive potential, the greater is the significance of year-to-year variability.

Our population model for the Niantic River winter flounder will use a temperature-dependent stock-recruitment relationship to generate year-classes whose size depend upon both the water temperature during larval development and the size of the spawning population. This particular representation of the recruitment process includes compensatory mortality (based on the stock-recruit model previously described) and will permit the introduction of realistic environmental variability related to the water temperature in February. Although the temperature variability will be simulated stochastically, this will be done using an empirical distribution derived from actual records of annual mean water temperatures in February. Because an earlier version of our stochastic population dynamics model was already described by Lorda et al. (1987), only the basic features of the updated version now under development are presented here.

The final model will describe the dynamics of an age-structured population of winter flounder with stochastic recruitment and compensatory mortality that occurs during the first year of the life of the fish. The model makes no assumptions about the stability of the population or its age structure, which can vary as a result of environmental variability introduced via the recruitment equations. Adult fish are subject to annual natural and fishing mortalities, and mature survivors spawn according to fecundity rates that depend on the age of the fish. Although a Leslie matrix formulation is used to carry the computations corresponding to these annual processes, its function is simply one of book-keeping. This is so because the size of each year-class is determined by the stochastic recruitment, and the Leslie matrix is only used to update the number of fish in each age-class at the end of each year. A box-and-arrow diagram of the underlying life-cycle simulation scheme is shown in Figure 37. The impact of larval entrainment is represented in this diagram as additional density-independent mortality in age-class 0. This mortality can be varied annually and the actual value will be based on estimates provided by the MIT larval dispersal and entrainment model. A sample of graphical model output corresponding to a simulation that assumes a 10% larval mortality due to entrainment is shown, for illustrative purposes only, in Figure 38. The vertical line at 35 years, represents the point in the simulation at which larval entrainment ceases and the population size begins its climb back to its initial level. This pattern of slow population decline while entrainment takes place, followed by a faster return to initial levels, is typical of populations in which compensatory mortality operates.

The basic inputs required by the model are: survival estimates for each larval stage, eggs, and age-class; fecundity rates for each age-class; an initial age-distribution for the adult population; estimated parameters of the recruitment model; estimates of the mean and variance of the water temperature during February in the Niantic River; and the estimated larval mortality due to plant entrainment. Except for the latter input (see discussion of the larval dispersion model), we have data for most of the other model inputs. However, better estimates of egg and larval mortality are still needed.

Long-term impact assessment

The larval dispersal and entrainment model together with the stochastic population model will allow us to simulate the long-term effect of larval entrainment at the adult population level under a variety of scenarios chosen to describe prevailing levels of entrainment, multiple or single sources of winter flounder larvae, and various levels of fishing effort. The final output from this simulation scheme will consist of time-series of expected population sizes suitable for estimating long-term averages and standard errors for direct comparisons, or for applying probabilistic risk analysis (PRA). In the latter case, projected population changes are expressed in terms of the probability that a postulated change (or no change at all) will occur in a specified number of years. Although both analytical methods are acceptable for impact assessment purposes, PRA methodology has been favored in recent environmental impact and risk assessment studies by the U.S. En-

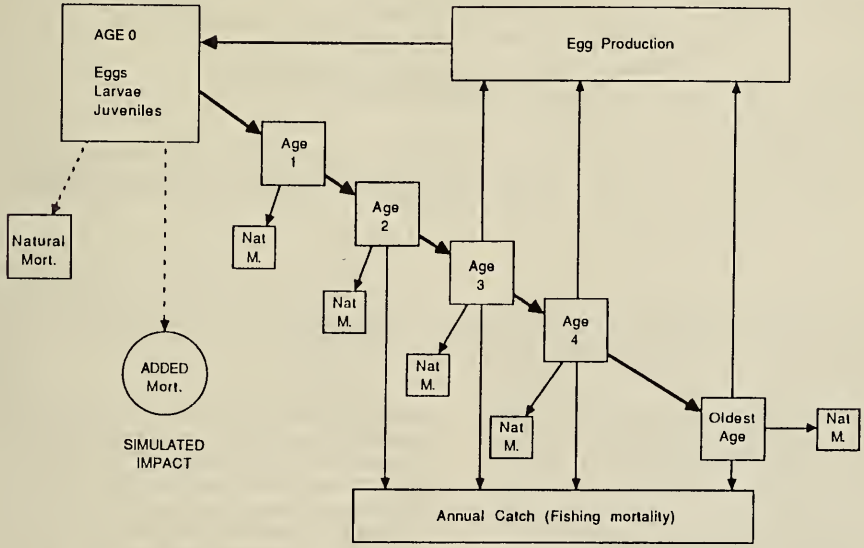


Fig. 37. Box and arrow diagram of the life-cycle simulation scheme in the population model. Transfers within the population (i.e., aging and reproduction) are indicated by thick arrows and occur once a year. Losses due to mortality are indicated by thin arrows and occur both daily (dashed) and yearly (thin solid).

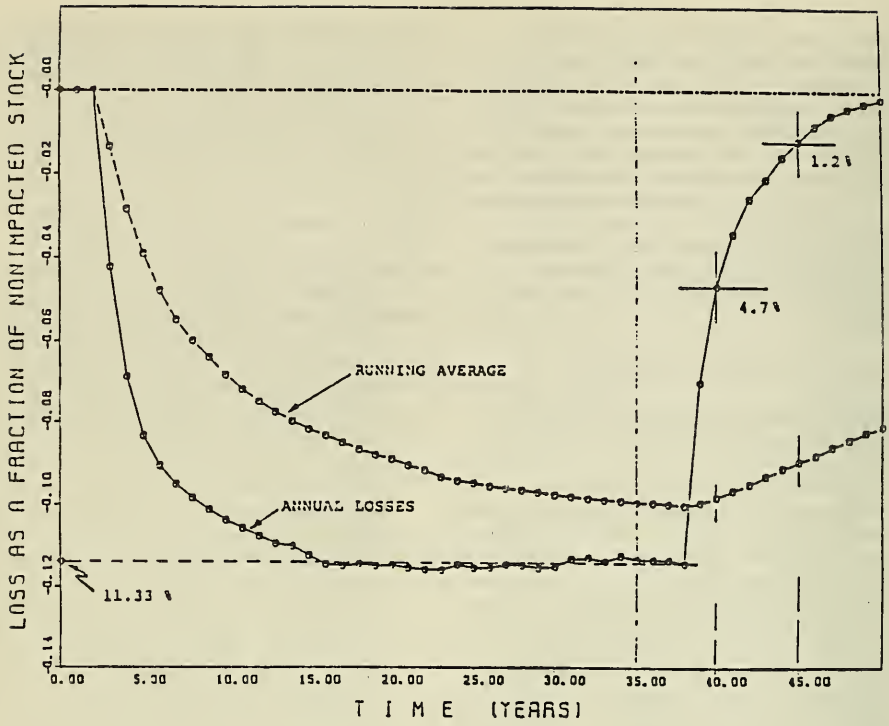


Fig. 38. Simulated power plant impact on winter flounder with a projected effect of 10% mortality over 35 years of plant operation followed by the recovery of population abundance.

vironmental Protection Agency. We hope to start preliminary work on this type of long-term impact assessment by the end of 1988.

While our data on the Niantic River winter flounder population is extensive, additional information is necessary to further refine MNPS assessment models. For example, the stock and recruitment relationship, larval mortality, and larval behavior are especially important for reliable population dynamics simulations. About two-thirds of the winter flounder larvae entrained each year at MNPS are in Stages 3 or 4 of development. Therefore, it remains necessary to determine how critical the loss of these larvae is to the population. To date, no relationship has been found between the absolute estimate of the number of larvae entrained and subsequent year-class strength (Fig. 39). However, the long-term effects of present levels of three-unit entrainment on the winter flounder population remain to be determined. In addition, detailed descriptions of larval move-

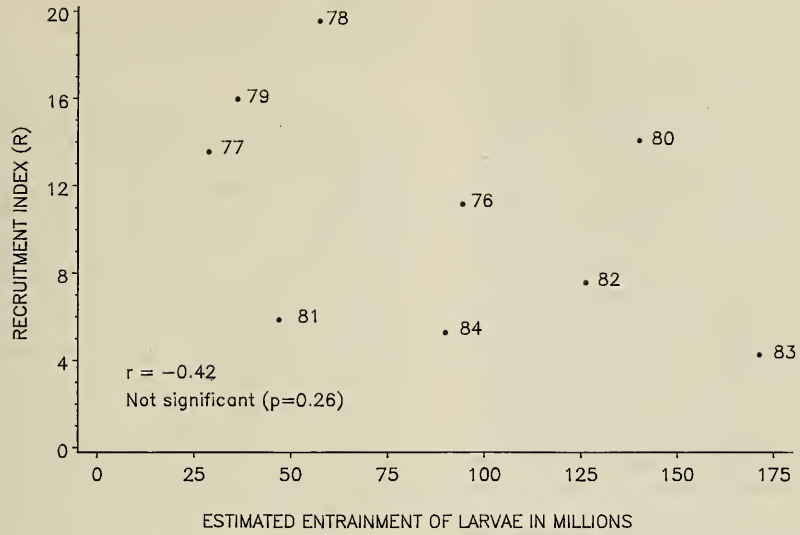


Fig. 39. Relationship between the annual age 3 recruitment index and annual estimated entrainment of winter flounder larvae at MNPS for the 1976 through 1984 year-classes.

ments, especially those flushed from the Niantic River, are needed. Also, little is known about the fate of larvae in Niantic Bay or the number removed from the area by tidal currents; the magnitude of larval metamorphosis in the bay; and whether or not post-larval young reside in the bay or are successful in moving into suitable nursery areas, such as the Niantic River. Larval aging is necessary to accurately determine rates of mortality and growth. The source of entrained larvae is not known with certainty. Although evidence from the larval sampling program suggests that the Niantic River is the likely source of most entrained larvae, drift of larvae from other areas of Long Island Sound into Niantic Bay cannot yet be ruled out. Sampling programs designed specifically to address the above concerns will be initiated in 1988 (NUSCO 1988a, 1988b).

Conclusions

Abundance of adult winter flounder in the study area around Millstone remained low in 1987, with numbers similar to those of 1984-86. The changes in abundance of local winter flounder during the past 12 years were similar to those taking place in other areas of Southern New England, as shown by significant correlations among the various abundance indices examined. This suggested that winter flounder populations were most likely affected by factors operating region-wide, which influenced reproduction and subsequent recruitment and, perhaps, from similar fishing pressures on the adult stocks. Historical records showed that the species has repeatedly fluctuated in numbers with periods of low and high abundance.

Several important developments in our winter flounder program this past year included the establishment of a stock and recruitment relationship and data analyses leading to increased knowledge of the dynamics of larval and juvenile stages. The three-parameter stock and recruitment model helped explain the variability seen in adult abundance and demonstrated that water temperature during spawning and early life history was as important as the parental stock size in determining recruitment success. Poor recruitment was associated with warmer-than-average years and strong year-classes were produced during cold years; this has also been found for a number of other winter-spawning marine fishes. Although strong environmental (i.e., density-independent) factors were implicated as important to winter flounder reproductive success, density-dependent mortality must also have been a significant stabilizing mechanism, given the relatively small range within which the absolute abundance of the winter flounder varies.

The use of the Gompertz function to describe larval abundance led to the finding that the κ parameter (i.e., the shape parameter determining the steepness of the Gompertz curve) described well the magnitude and breadth of larval distribution over time (see Figure 23). This parameter was found to be directly related to February water temperatures, with larger κ values associated with warmer years and smaller values for colder years. This illustrated that in a cold year, larval abundance, as characterized by the Gompertz function, was slow in reaching a peak and had a more broadly based abundance curve. Conversely, in a warm year the curve peaked quickly and had a narrow base. A highly significant relationship was found between the κ parameter and winter flounder recruits 3 years later (see Figure 24). This implied that in cold years somewhat fewer larvae were present at any one time, but the season was longer in duration; the result was a stronger year-class. The February temperatures would have most likely affected spawning and egg incubation, resulting in protracted spawning and longer time to hatching. With larvae less concentrated over time, effects of predation upon larvae may have been less and there likely would have been a better chance for larvae to encounter adequate food densities. However, exact causal mechanisms are still unknown.

Results of both the larval analyses and the three-parameter stock-recruitment model showed that year-class strength was related to events in the early life history of the winter flounder, for which water temperature was an important factor (by itself or as a surrogate for other factors). Just as the stock and recruitment relationship was used to describe recruitment as a function of adult stock and February temperatures, the relationship found between the κ parameter and the age 3 recruitment index can be used as a second and independent indicator of future adult recruitment. The empirical relationship between κ and the age 3 recruitment index (R) given on Figure 24 was used to approximate recruitment levels from 1976 through 1984 (Fig. 40). For the following 3 years, recruitment from the 1985 year-class was predicted to be greater than from the 1986 and 1987 year-classes and and close to the recruitment from the 1977 and 1980 year-classes. Very similar predictions were made for the same 3 years using the three-parameter stock and recruitment relationship (see Figure 15), although somewhat smaller differences in recruitment were predicted.

Results of the larval sampling program showed the greatest mortality occurring during Stage 2 of development in the Niantic River. During this stage, which is characterized by the transition from yolk-sac larvae to first feeding and limited mobility, is also when most larvae are flushed from the river and when most jellyfish predation may occur on larvae remaining in the upper river. All of this suggests that density-dependent mortality probably occurs during this stage of larval development.

Van der Veer (1986) pointed out that, for plaice, the highest coefficients of variation for yearly abundance estimates of different life stages occurred during larval development in late winter and first settlement of pelagic juveniles in spring. Much less variation was seen for post-larval young during mid-summer and for age 2 recruits. He

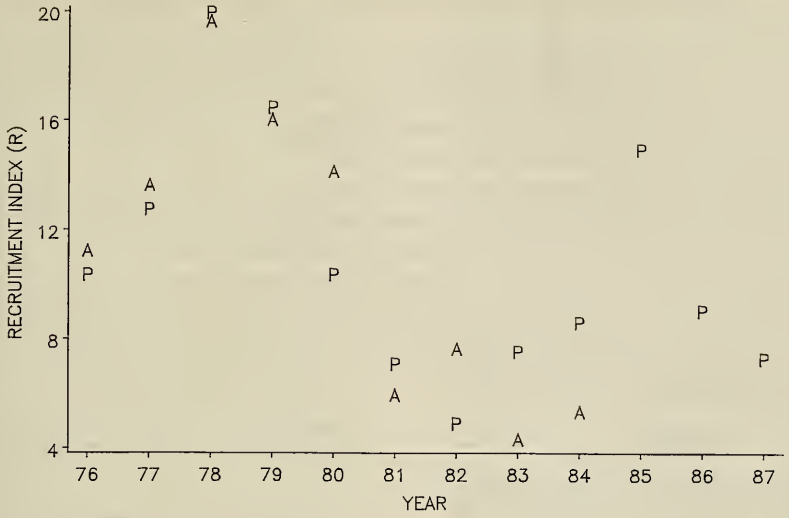


Fig. 40. Actual values (A) for the annual age 3 recruitment index (R) compared to predicted values (P) determined from the relationship between the κ parameter of the Gompertz function fitted to annual cumulative entrainment densities (see Figure 24).

attributed the sharp decline in variation of abundance for older juveniles to a density-dependent regulatory mechanism occurring during and shortly after larval settlement. The coefficients of variation determined for indices of abundance for various life stages of Niantic river winter flounder are shown in Table 19. Although larval and juvenile data were relatively sparse, remarkably similar coefficients were found for nearly all life stages. The only exception was Stage 2 larvae, which had the largest CV, further supporting the notion that compensatory mortality probably occurs during this early period of winter flounder life history.

The models currently under development for MNPS impact assessment will incorporate estimates and variability of population parameters, hydrodynamics of the waters in the Millstone area, and elements that realistically mimic larval behavior. Once finalized, the model features or inputs will be updated as soon as more complete data are available. The direction of research in the future will, in many cases, be governed by the need to obtain specific information necessary for the assessments. Sustained monitoring coupled with specific new sampling programs in 1988 and a completed impact assessment model will further lead towards the resolution and quantification of MNPS impact on the winter flounder.

TABLE 19. Coefficients of variation (CV) for abundance indices of various life stages of Niantic River winter flounder.

Life stage	Abundance index used	N[a]	CV
Eggs	Relative index of egg production	11	63
Stage 1 larvae	α parameter of Gompertz function	4	63
Stage 2 larvae	α parameter of Gompertz function	4	114
Stage 3 larvae	α parameter of Gompertz function	5	57
Stage 4 larvae	α parameter of Gompertz function	5	45
Early juvenile	Mean CPUE at station LR (mid-June-early July)	5	51
Late juvenile	Mean CPUE at station LR (late August-September)	5	55
Age 3 recruits	Age 3 recruitment index (R)	9	47
Adults	Parental stock index (P)	12	43

[a] Number of observations.

Summary

1. Indices of abundance estimates (Jolly composite abundance index and trawl CPUE) of the Niantic River spawning population of adult winter flounder have been made since 1976. The 1987 abundance survey had the latest start since 1980 because of ice cover in the river. The 1987 Jolly index showed a slight increase over the 12-year low abundance index of 1986, but remained below the levels of abundance from previous years. The 1987 median trawl CPUE also increased over 1986. This median was similar in magnitude to those for 1984 and 1985, but was only 30-60% of CPUE values for 1976-83.

2. Median CPUE values of juvenile (< 15 cm) winter flounder taken during the adult surveys were very low in 1986 and 1987. The small values implied poor reproductive success in recent years. However, factors such as differential distribution among the Niantic River sampling stations probably affected this index of abundance.

3. Annual δ-mean CPUE values were computed for the first time for all winter flounder taken by the trawl monitoring program (TMP) from 1976 through 1986. The δ-mean abundances did not perfectly track the Niantic River median CPUE values. The peak in δ-means persisted from 1977 through 1983 and was not as pronounced as it was in the Niantic River. The 1985 and 1986 δ-means were greater than those in 1977 and 1978, whereas for the Niantic River medians the opposite was true.

4. The TMP catches were mostly made up by fish larger than 15 cm (55-75%). However, smaller fish predominated from January through April. Catch of the latter fluctuated less outside of the Niantic River during the spawning season than inside and δ-means for 1986 and 1987 suggested that juvenile abundance was not as low as the Niantic River median CPUE for these fish would have indicated.

5. Annual Niantic River median CPUE values and TMP δ-means were compared to other regional indices of abundance. With few exceptions, most indices were significantly correlated and thus described real trends in abundance that occurred throughout Southern New England.

6. Examination of available historical data (commercial fishing CPUE for Rhode Island and a URI trawl time-series) showed that winter flounder abundance typically fluctuated with sharp increases in catch most likely related to the occurrence of one or more particularly strong year-classes in succession.

7. For the first time in the past 11 years, more males than females were taken during the Niantic River surveys in 1986 and 1987.

8. The length of females at 50% sexual maturation was 26.8 cm, when fish were 3 or 4 years old. Most spawning in the Niantic River was completed by late March or early April. Spawning appeared to have been related to water temperature as in relatively cold years proportionately fewer females spawned earlier during the season than in warmer years.

9. Based on the abundance indices of females and their size distribution, a yearly index of egg production was determined. This index peaked in 1982 and has declined about 80% since then. However, adult abundance and absolute egg production were not the only factors in determining year-class strength.

10. The 12 years of Niantic River winter flounder relative abundance data were used with a Ricker stock-recruitment model. Parental stock was defined as all winter flounder age 3 and older and recruits were those fish turning 3 years old each spawning season. The two-parameter Ricker model did not explain much of the variability (44%) seen in annual recruitment. However, annual February water temperatures were found to be significantly and inversely correlated with recruitment indices. The addition of a temperature parameter to the model resulted in a much improved fit to the observed data ($R^2 = 0.78$) and helped to explain large differences seen in recruitment for similar parental stock sizes. Although the actual mechanisms affecting winter flounder recruitment were unknown, the February water temperature appeared to have been related to those factors.

11. Larval winter flounder studies have been conducted in Niantic River and Bay since 1983 and entrainment collections have been made since 1976. In 1986 and 1987, peak abundance of larvae occurred first in the river and, after a lag, in the bay. Comparison of the dates of peak abundance showed that most flushing of larvae from the river to the bay occurred during Stage 2 of development.

12. An apparently higher mortality of larvae was found in 1987 compared to the previous year; this occurred early in the season, when the majority of the larvae were in the river. Effects of predation by jellyfish was not as apparent in 1986 and 1987 as it had been in previous years. Examination of length-frequency distributions indicated that most mortality occurred during the 3 to 4-mm size-class, suggesting that this was a critical period for mortality. Annual total mortality rates were estimated from the difference between the abundances of larvae at 3 and 7 mm in length. For 1983-87, these estimates ranged from 84.6 to 96.9%.

13. In entrainment samples, Stage 3 larvae dominated. As expected, total entrainment estimates for 1987 following the startup of MNPS Unit 3 were among the highest during the last 12 years, even though the median density (number per 500 m^3) was among the lowest. Entrainment estimates were dependent upon plant operating conditions as well as larval densities each year. The dates of peak abundance for entrainment samples were positively correlated with March and April water temperatures.

14. From the 12 years of entrainment data, the shape of the abundance curve, as measured by the κ parameter of the Gompertz function, was found to be a good predictor of subsequent recruitment of age 3 winter flounder. The shape of the abundance curve was related

to February water temperatures, with a narrow, high-peaked curve found during warmer years (low recruitment) and a broad, flatter curve during colder years (high recruitment).

15. Laboratory studies showed that larval growth rates were dependent upon water temperature. These studies suggested that the optimum temperatures for growth were intermediate (6.9-7.5°C), with decreased growth occurring at lower (5.4°C) or higher (10.8°) temperatures.

16. Yearly growth rates were estimated using field data since 1983 at station C in the Niantic River and since 1976 for entrainment data. Estimated growth rates were consistent with laboratory estimates, again showing that growth was dependent upon water temperatures.

17. Post-larval young-of-the-year winter flounder have been sampled at two stations in the Niantic River since 1983. Densities at station LR in 1987 were higher than in previous years. Smaller differences in growth were noted between stations LR and WA during 1986 and 1987 than during 1984 and 1985. Differences among years may have been due to density-dependent growth, especially at LR. Survival rates were very similar among years, regardless of densities of young.

18. The winter flounder was the second-most abundant fish impinged on the traveling screens at MNPS since 1976. Relatively few specimens were impinged at Unit 2 during the past 3 years due to declining abundance, varying plant operations, and possible reductions related to the construction and operation of Unit 3. The installation of fish return sluiceways at Units 1 and 3 lessened the impact of impingement on the winter flounder because it has good (> 85%) survival when returned to the water. Routine impingement monitoring at Unit 2 was discontinued in December 1987 upon agreement between NU and CT DEP.

19. To predict the long-term effects of larval entrainment, an impact assessment model for winter flounder is currently under development, which includes hydrodynamics and population dynamics submodels. The function of each submodel is the estimation of the fraction of total larval production lost to entrainment at the plant and the measurement of any resulting population changes, respectively. A newer, more accurate and detailed hydrodynamics submodel is under development at MIT. Larval behavior will be simulated to correspond more realistically to observations made in the field. A stochastic age-structured population submodel will incorporate the three-parameter stock-recruitment relationship, which includes a measure of compensatory mortality and the introduction of realistic environmental variability.

20. Results from both larval analyses and the three-parameter stock-recruitment relationship showed that year-class strength was related to events in the early life history stages, with colder winters associated with better reproductive success. Greatest winter flounder mortality took place during Stage 2 of development, during which density-dependent mortality probably occurred.

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Erratum

NUSCO (1987): The intercept for the length-weight relationship for Niantic River winter flounder found on Table 10 in this report should have been -2.2636 instead of the value of -2.2261 that was given.

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Exposure Panel Program

Introduction

The Exposure Panel Program was designed to determine what effect the operation of Millstone Nuclear Power Station (MNPS) has on the abundance and distribution of marine woodborers, and the rate of wood degradation in the marine ecosystem of Long Island Sound (LIS). Two groups of marine woodborers are common in these waters. The first group consists of small crustaceans, isopods (*Limnoria* spp.) and amphipods (*Chelura terebrans*), which make shallow tunnels and excavations in the surfaces of submerged wood. The second group consists of the more destructive shipworms *Teredo navalis* and *Teredo bartschi*, which are molluscs that penetrate the surface of wood as larvae (pediveligers) prior to metamorphosing into their adult, wormlike form. Woodborers are very important ecologically because they decompose wood entering estuarine, coastal and deep ocean areas (Turner 1984). However, they also cause destruction of man-made structures.

Particular attention has been paid in recent years to the response of woodborer populations exposed to heated effluents from power plants, because elevated temperatures may increase growth, reproduction, and survival of woodborers, all of which contribute to accelerated destruction of wooden structures (Naylor 1965; Turner 1973; Hoagland 1981). These effects were seen near Jersey Central Power and Light Company's Oyster Creek Nuclear Generating Station, where destruction of docks at nearby marinas was attributed to increased woodborer activity in the effluent (Turner 1973; Hoagland and Turner 1980; Macieolek-Blake et al. 1981). The objectives of the MNPS Exposure Panel Program are:

1. to monitor the abundance of marine woodborers at five sites in the Millstone Point area,

2. to quantify the loss of wood associated with the presence of woodborer populations in the vicinity of MNPS,

3. to monitor the dispersal of *Teredo bartschi* in terms of distance from the Millstone Quarry, and,

4. to monitor the abundance of prevalent fouling organisms, and to investigate their relationship to woodborer abundances in the Millstone Point area.

To achieve these objectives, three separate studies were conducted. The first (Exposure Panel Study) used exposure panels to monitor the abundance of fouling and wood-boring species, as well as the associated wood-loss. The second study (Distribution Study) used exposure panels deployed in close proximity to the MNPS discharge to monitor the density of *Teredo navalis* and *Teredo bartschi* relative to the distance from the thermal discharge. The third study (Timber Study) used commonly available dock building materials to quantify wood-loss.

Development of these studies, and results prior to 3-unit operation (1968-1986), are summarized in NUSCO (1987). This report represents an initial assessment of the effects of 3-unit operation on marine woodborers, based on results from the Exposure Panel Study and the Distribution Study. Results from the Timber Study will be presented in a future report, scheduled for 1989.

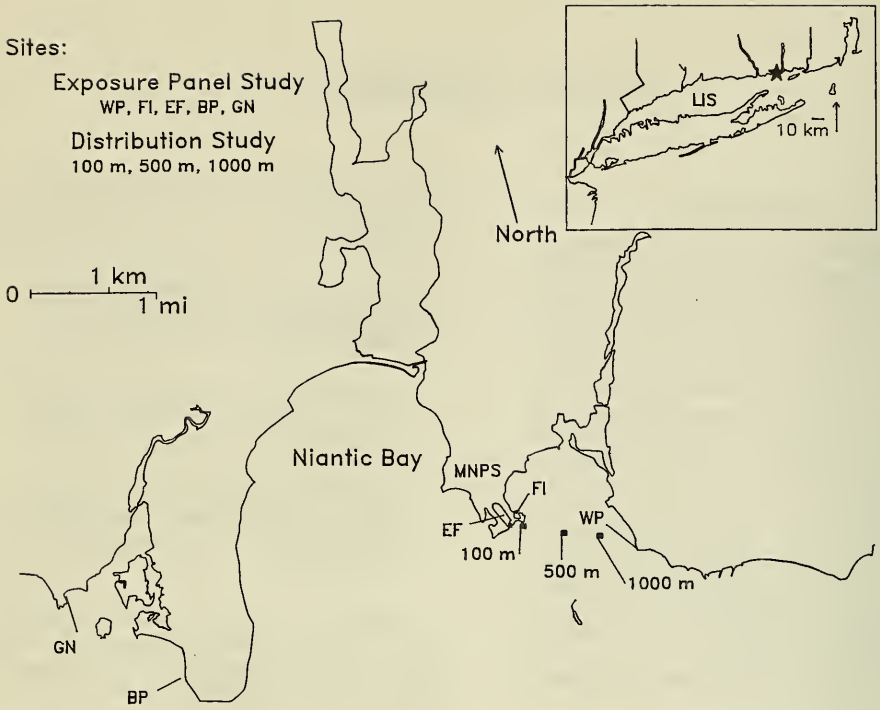

Fig. 1. Location of exposure panel sites in the vicinity of the Millstone Nuclear Power Station (WP = White Point, FI = Fox Island, EF = Effluent, BP = Black Point, GN = Giants Neck, 100 m = trawl-line at 100 m, 500 m = trawl-line at 500 m, 1000 m = trawl-line at 1000 m).

Exposure Panel Study

Materials and Methods

Seawater Temperature

Seawater temperature data during each exposure period at several of the sites near MNPS have been summarized. Water temperatures were derived from the EDAN (Environmental Data Acquisition Network) system, which continually records a variety of environmental parameters at 15-minute intervals. Ambient water temperatures were recorded by sensors in Unit 1 and Unit 2 intake bays, and effluent water temperatures by sensors in the quarry cuts. Prior to 1987, temperatures at White Point and Fox Island were measured continuously with thermistors and either strip or circle chart recorders. In 1987, these data were collected using solid state data loggers.

Sampling Procedure

The present study used sets of six replicated wood panels submerged at five sites: White Point (WP), Fox Island (FI), Black Point (BP), Giants Neck (GN), and Effluent (EF), which was in the Millstone Quarry where panels were exposed to maximum discharge water temperatures (Fig. 1).

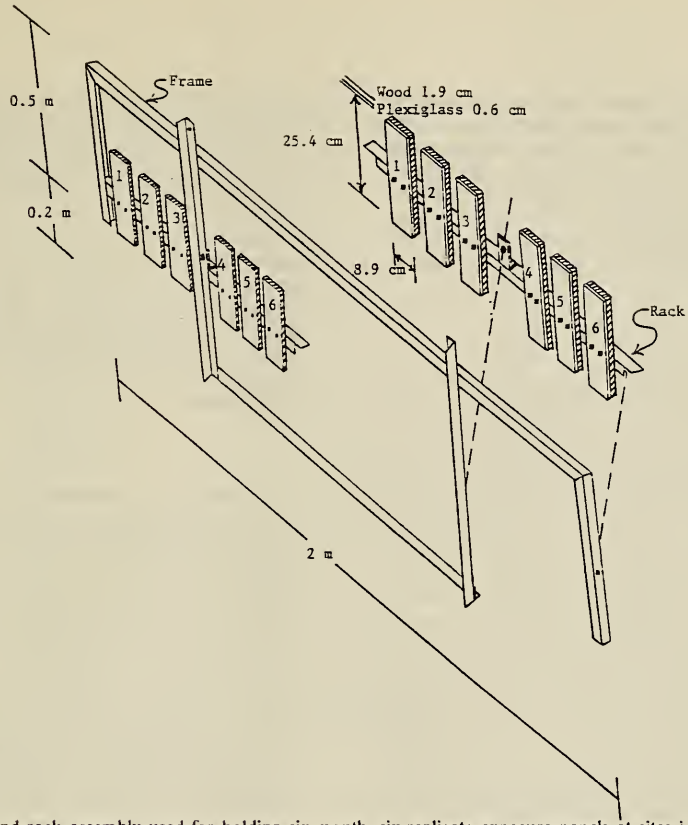

Fig. 2. Frame and rack assembly used for holding six-month, six-replicate exposure panels at sites in the vicinity of the Millstone Nuclear Power Station.

Each exposure panel was a knot-free pine board (25.4 x 8.9 x 1.9 cm) with one face covered by plexiglass. Only the uncovered wood side of each panel was processed. Two sets of six replicated panels were bolted to a stainless steel rack attached to a stainless steel frame at each site (Fig. 2). The rack and frame assemblies deployed at WP, FI, BP, and GN were suspended from docks by ropes in waters not exceeding 2 m in depth; the lower edge of the panels was maintained 0.2 m off the bottom. At EF, two rack and frame assemblies were used; the first (ES) was 1 m below the surface, and the second (EB) about 1 m off the bottom at high tide, at a depth of 10 m. The panels at EB were moved in May 1987 to the cantilever dock leading to the Floating Lab, a location used for exposure panels prior to 1979. At this new location, the EB panels are maintained in shallow water 0.2 m off the bottom, as at the other sites.

The panels were placed at each site in February, May, August and November and collected six months later in August, November, February and May, respectively. This provided four exposure periods, each overlapping the next by three

months. At the start of each exposure period, one rack of panels was removed for processing and a new rack with fresh panels was deployed. Throughout this report the exposure periods will be referred to using the following abbreviations: Feb-Aug, May-Nov, Aug-Feb and Nov-May. Each abbreviation refers to the month of panel deployment followed by the month of panel collection.

Sample Processing

After collection, panels were either refrigerated at 5 °C and processed immediately or frozen and processed at a later time. Primary cover, as a percentage, was estimated for each organism that occupied more than 1% of the panel surface, e.g., barnacles, bryozoans, tunicates and some algae. Beginning in 1980, cover was estimated for freespace, mud and the dead tests of fouling species, to complete the description of total primary cover for each panel. Numerical abundance was determined for barnacles and mussels by counting the individuals on each panel. If the number of individuals per panel exceeded 100, six subsamples of 1 x 1 inch were randomly selected, three from the upper half and three from the lower half of the panel. In 1981, only the asbestos side (currently replaced by plexiglass) of each exposure panel was used for determining numerical abundance of fouling species; therefore, numerical abundance data for barnacles and mussels were not recorded for the wood panels in 1981.

The abundance of woodborers was determined after the panel had been scraped of fouling species. All individuals of the genera *Limnoria* and *Chelura* were counted when densities were less than 100 individuals per panel; otherwise, the subsampling scheme previously described for barnacles and mussels was used. Subsampling was always conducted evenly between the top and the bottom halves so that approximately 100 individuals were collected from each panel. After assessing the limnorid and chelurid abundances, panels were frozen and subsequently examined by means of X-ray photography (80 kV, 5 mA, for 1.2 min). The radiographs were used to count the number of shipworms, *Teredo navalis* and *T. bartschi*, and visually estimate the percentage of wood lost per panel. The percentage of wood lost was determined by rating the general proportions of bright areas, caused by various densities of shipworm tubes and the dark areas caused by various degrees of wood-loss. To determine the species of shipworms collected, shipworms were randomly removed from the panels until all or at least 100 individuals were identified from each site. Shipworms smaller than 5 mm in length were classified as *Teredo* juveniles because their pallets were too small and undeveloped to allow accurate identifications.

Data Analysis

The first set of exposure panels for which results are presented in this report was deployed in November 1978, and the last set was collected in August 1987. Each exposure period is represented, therefore, by six panels replicated over years, a maximum of four times during 2-unit operation, and one or two times during 3-unit operation. The actual numbers of panels processed for each site/exposure period combination are presented in Table 1. Unit 3 began commercial operation on April 23, 1986, and although some intermittent operation and testing of circulation pumps occurred before this date, we have considered all sampling periods from Nov-May of 1979 to Nov-May of 1986 as 2-unit operation. The monitoring of all panels was suspended from November 1981 to February 1985 to investigate the life histories of two shipworms, *Teredo navalis* and *T. bartschi* in relation to seawater temperature.

All averages and other summary statistics for each taxon were computed by exposure period. Temperature data were averaged by month. Percentage of primary cover and counts of individuals were summarized as means. Data provided in histograms were summarized by year within each exposure period, while corresponding tables compare data collected before vs. after 3-unit operation. This format represents the annual variability as well as the differences between 2-unit and 3-unit operational periods.

TABLE 1. The total number of panels used in comparisons for the time periods of 'before' (B = panels collected from May 1979 to May 1986) versus 'after' (A = panels collected from August 1986 to August 1987) three-unit operation at the Millstone Nuclear Power Station, nominally 6 panels/exposure period/year.

PARAMETER	SITE	EXPOSURE PERIOD							
		Aug - Feb		Nov - May		Feb - Aug		May - Nov	
		B	A	B	A	B	A	B	A
Primary cover and counts of Woodborers	Effluent bottom	6	6	6	6	6	12	6	6
	Effluent surface	18	6	24	6	24	12	24	6
	Black Point	3[a]	5[b]	6	6	0[c]	12	0[a]	6
	Giants Neck	18	6	24	6	24	12	24	6
	Fox Island	18	6	24	6	18[c]	12	18[c]	6
	White Point	18	6	24	6	24	12	23[a]	6
Counts of Barnacles and Mussels	Effluent bottom	6	6	6	6	6	12	6	6
	Effluent surface	12	6	18	6	18	12	18	6
	Black Point	3[a]	5[b]	6	6	0[c]	12	0[a]	6
	Giants Neck	12	6	18	6	18	12	18	6
	Fox Island	12	6	18	6	12[c]	12	12[c]	6
	White Point	12	6	18	6	18	12	17[a]	6

[a]Some panels lost, attributed to Hurricane Gloria (Sept. 1985).

[b]One panel lost from frame and rack assembly.

[c]Panels inadvertently exposed for 3 months or 9 months excluded from analyses.

Percentage of wood lost from panels in 1979 was based on visual assessments made while splitting the panels in search of shipworms. From 1980 to 1987 wood-loss was based on percentages derived from radiographs, which correlated well (r^2 = 0.98) with panel weight loss data (NUSCo 1987).

Results

Seawater Temperatures

Each of the four exposure periods was characterized by a different water temperature regime (Fig. 3). The seawater temperatures during the Feb-Aug and Aug-Feb exposure periods are best described by their ranges because temperatures continually increase and decrease, respectively. Feb-Aug began when ambient water temperatures (measured at MNPS intakes) were coldest (< 3 °C) and ended when water temperatures were warmest (> 20 °C). Its converse, the Aug-Feb period started with warm temperatures and ended with cold. Seawater temperatures during the May-Nov and Nov-May exposure periods are more appropriately described by average values because they are composed of the warmest (average = approx. 16 °C) and coldest (average = approx. 7 °C) months of the year, respectively. Panels at the effluent sites (EB, ES) were exposed to undiluted thermal effluent; since 1978, effluent temperatures have averaged 9-11 °C above ambient, and maximum ΔT's were in the range of

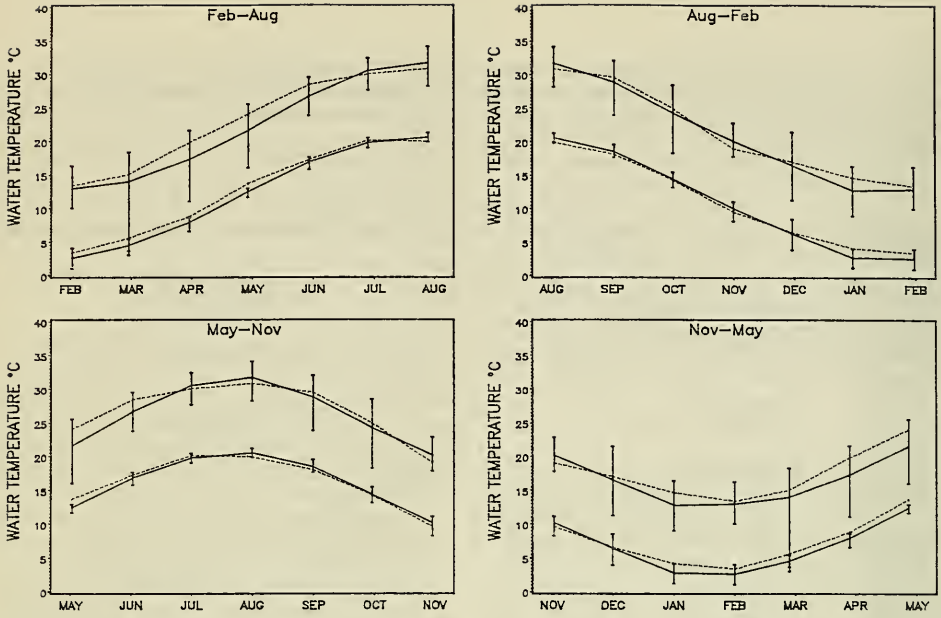

Fig. 3. The average monthly seawater temperatures at the Unit 1 & 2 intakes (ambient, bottom pair of lines in each graph) and the Millstone Quarry cuts (effluent, the top pair of lines in each graph) during the four six-month exposure periods. The monthly averages are from the 15th of one month to the 15th of the next (--- average temperatures during 3-unit operation, — average temperatures from November 1978 to May 1986, vertical bars represent the range of average monthly temperatures over this seven and one half year period of 2-unit operation).

12-15 °C.

Effluent temperature regimes (i.e., annual temperature ranges) have not changed substantially since Unit 3 began operation; however, the volume of cooling water has almost doubled. Prior to 1986, sampling sites at WP, FI, BP, and GN were unaffected by the MNPS thermal plume; annual average temperatures at these sites were within 0.6 °C of those at the intakes. From early spring through early autumn, temperatures at the FI sampling site were up to 2 °C above ambient, but these elevated temperatures were attributed to natural warming of shallow waters in Jordan Cove by solar radiation. Similar insolation of shallow estuaries has been reported elsewhere (Dale and Gillespie 1977; Dean and Officer 1977; de Wilde and Berghuis 1979).

Since Unit 3 began operation, the added volume of cooling water has increased the areal extent of the MNPS thermal plume, which on an ebbing tide raises water temperatures in Jordan Cove (see the Hydrothermal Studies section of this report). During 3-unit operation in 1987, water temperatures at FI and WP were close to ambient during most of the tidal cycle (9-10 h), but maximum ΔT's of 2-4 °C occurred for 2-3 hours per cycle (Fig. 4). Insolation in summer might raise temperatures an additional 2 °C.

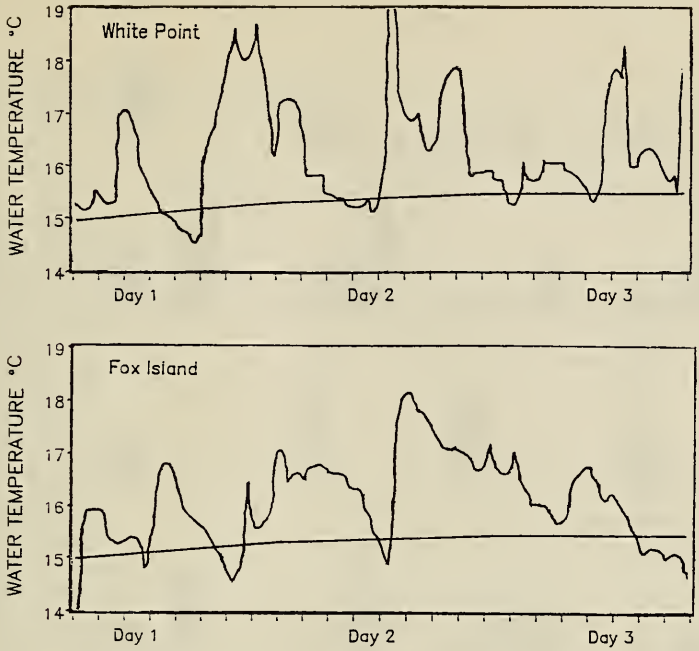

Fig. 4. Seawater temperatures at White Point and Fox Island from October 15-17, 1987 during 3-unit operating conditions. The solid line across the bottom of each graph represents the daily mean temperatures as recorded at Unit 1 & 2 intakes.

Fouling Species

Percent cover. The percentage of panel surfaces covered by fouling organisms varied among sites and years and between operational periods (Fig. 5). Average values ranged from 95.5% at FI in Nov-May 1987 to < 1% at WP and GN in Aug-Feb 1986. In general, highest percentages occurred at BP and FI, and lowest at EB. The remainder of the panel surfaces was free space, or covered by the calcareous remains of dead barnacles or bryozoans (these dead remains occupied up to 40% cover; Fig. 5).

Almost 300 species of plants and animals, including both motile and sessile members of the local fouling community, have been identified during the exposure panel study (NUSCO 1982). Present studies focus on the sessile assemblages because these are more likely to influence woodborer abundances (cf. Nair and Saraswathy 1971). Of these, only 22 taxa (3 plant and 19 animal) occupied a mean of 1% or more of the panel surface at any site during any exposure period, during 2-unit or 3-unit operation. The abundances of these 22 taxa are presented in Table 2.

These species exhibited different spatial and temporal patterns of distribution. Some species were ubiquitous, found at all sites in both operational periods, e.g., *Balanus crenatus*, especially abundant in the Nov-May exposure period.

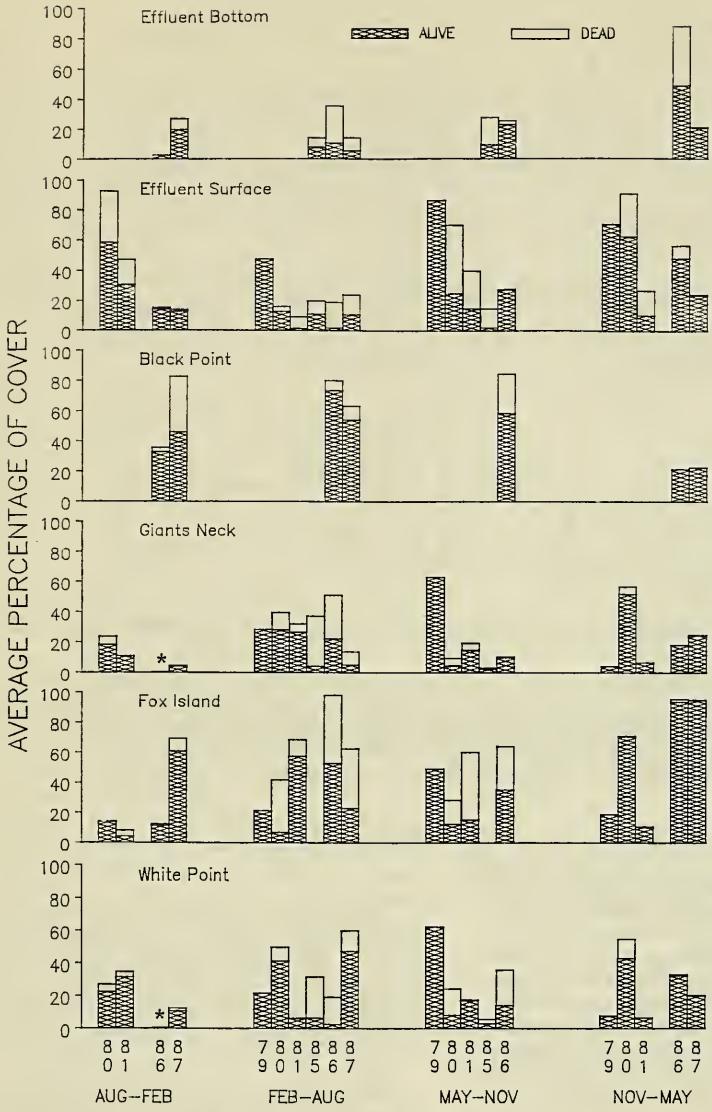

Fig. 5. Mean % cover of sessile fouling organisms on exposure panels collected from 1979-1987. Histograms reflect the total percentage of cover, which was comprised of both living plant and animals and their dead remains (* = values < 1%).

TABLE 2. Mean % cover of the most prevalent fouling organisms on exposure panels before (B) and after (A) three-unit operation at MNPS.

SITE	TAXON	EXPOSURE PERIOD Aug - Feb B	Aug - Feb A	Nov - May B	Nov - May A	Feb - Aug B	Feb - Aug A	May - Nov B	May - Nov A
EB	*Alcyonidium* spp.	---[a]	---	17.8	t[b]	---	---	---	---
	Anomia simplex	---	1.3	---	---	---	---	---	---
	Balanus crenatus	t	---	23.7	7.7	---	t	---	---
	Balanus eburneus	---	1.5	---	---	1.3	t	8.7	9.0
	Balanus improvisus	---	t	---	---	t	t	t	1.3
	Balanus juveniles	---	---	---	1.0	t	1.1	---	1.7
	Bugula spp.	---	11.3	---	2.5	---	2.8	---	7.0
	Metridium senile	---	t	---	---	5.0	1.0	---	---
	Mycale fibrexilis	---	---	---	---	---	---	---	3.3
	Mytilus edulis	---	t	6.3	5.8	---	---	---	---
	Serpulid tubes	t	1.3	---	---	---	t	t	---
	Tubularia crocea	---	---	---	1.2	---	---	---	---
ES	*Alcyonidium* spp.	---	---	9.2	---	---	---	---	---
	Balanus crenatus	t	---	10.7	3.0	t	---	---	t
	Balanus eburneus	2.7	t	---	---	3.5	2.6	9.2	3.5
	Balanus improvisus	22.2	t	3.4	---	9.9	t	11.8	1.0
	Balanus juveniles	1.0	---	1.8	---	1.6	t	10.3	t
	Bugula spp.	t	9.0	---	2.7	t	---	---	t
	Halichondria spp.	---	t	---	---	---	1.8	---	---
	Metridium senile	---	---	---	t	1.5	t	---	---
	Mycale fibrexilis	---	---	---	---	---	---	---	21.3
	Mytilus edulis	1.6	1.0	17.8	16.0	---	---	---	---
	Tubularia crocea	1.5	---	3.8	t	t	---	t	---
BP	*Balanus balanoides*	---	---	---	---	ns[c]	37.8	ns	---
	Balanus crenatus	---	---	6.7	3.0	ns	15.5	ns	---
	Balanus eburneus	---	t	---	---	ns	t	ns	4.7
	Balanus improvisus	---	t	2.0	---	ns	t	ns	1.3
	Balanus juveniles	---	---	4.0	15.2	ns	t	ns	---
	Botryllus schlosseri	2.4	5.6	---	---	ns	t	ns	t
	Codium fragile	27.3	t	---	---	ns	---	ns	---
	Cryptosula pallasiana	1.7	19.6	---	---	ns	1.3	ns	20.8
	Derbesia marina	---	12.8	---	---	ns	---	ns	3.8
	Halichondria spp.	---	---	---	---	ns	t	ns	2.0
	Laminaria saccharina	---	---	8.8	4.5	ns	---	ns	---
	Schizoporella errata	---	7.0	---	---	ns	4.5	ns	24.5

TABLE 2. (cont'd)

SITE	TAXA	EXPOSURE PERIOD							
		Aug - Feb		Nov - May		Feb - Aug		May - Nov	
		B	A	B	A	B	A	B	A
GN	*Balanus amphitrite*	t	---	---	---	t	---	1.7	---
	Balanus balanoides	---	---	---	---	---	4.9	---	---
	Balanus crenatus	---	---	11.4	2.7	13.9	6.5	1.4	---
	Balanus eburneus	---	---	---	---	t	---	4.9	---
	Balanus improvisus	t	---	---	---	t	t	1.5	---
	Balanus juveniles	t	---	6.3	20.3	t	t	3.2	---
	Botryllus schlosseri	4.8	---	---	---	2.5	---	0.6	---
	Cryptosula pallasiana	t	t	---	---	t	t	3.3	1.0
	Derbesia marina	---	1.0	---	---	---	---	---	2.4
	Halichondria spp.	---	---	---	---	t	---	1.1	t
	Laminaria saccharina	---	---	2.3	1.7	t	t	---	---
	Schizoporella errata	---	1.0	---	---	---	t	t	5.5
FI	*Balanus balanoides*	---	---	---	---	---	26.1	---	---
	Balanus crenatus	t	---	35.2	79.8	14.3	8.7	t	---
	Balanus eburneus	---	---	---	---	t	---	1.1	---
	Balanus improvisus	t	t	---	---	1.0	---	2.0	t
	Balanus juveniles	t	1.3	12.1	15.0	t	t	1.3	t
	Botryllus schlosseri	1.1	---	---	---	t	t	---	---
	Bugula spp.	t	t	---	---	t	t	1.0	3.9
	Cryptosula pallasiana	6.0	56.8	---	---	6.0	t	14.4	29.2
	Schizoporella errata	---	---	---	---	---	1.0	---	---
WP	*Balanus crenatus*	---	---	10.8	5.8	6.6	22.1	---	---
	Balanus eburneus	---	---	---	---	2.9	---	5.9	---
	Balanus improvisus	1.2	---	t	---	1.2	---	1.2	---
	Balanus juveniles	t	---	4.6	12.5	t	t	2.2	---
	Botryllus schlosseri	12.0	---	---	---	1.3	---	t	---
	Bugula spp.	---	---	---	---	1.7	1.3	1.1	---
	Cryptosula pallasiana	2.4	4.3	---	---	1.8	t	6.5	2.9
	Derbesia marina	---	3.7	---	---	---	---	---	t
	Halichondria spp.	---	---	---	---	---	t	1.5	0.7
	Laminaria saccharina	---	---	5.8	1.2	---	---	---	---
	Schizoporella errata	---	---	---	---	t	---	1.4	6.8
	Scypha spp.	---	---	---	---	---	---	---	1.2

[a] (---) = taxon has never occurred on a panel

[b] (t) = trace percentage cover, < 1% of the panel's surface

[c] (ns) = exposure period not sampled

Balanus improvisus was found at all sites, but was abundant only at ES before 3-unit operation. Other species found during both operational periods were consistent components of the fouling communities at only effluent sites (EB, ES), e.g., *Mytilus edulis*, or at only ambient sites (WP, FI, BP, GN), e.g., *Cryptosula pallasiana* and *Laminaria saccharina*. Still other species had

more restricted distributions, e.g., *Codium fragile* only at BP, and *Alcyonidium* spp. and *Tubularia crocea* only at effluent sites during 2-unit operation, or *Mycale fibrexilis* at ES, and *Balanus balanoides* at ambient sites during 3-unit operation. *Balanus balanoides* is typically an intertidal barnacle; its presence on subtidal panels is unpredictable. For example, Battelle researchers (1968-1978) found 65-70% cover of *B. balanoides* in 1970 and 1971 at GN, and less than 2% in all other years (Battelle, unpublished data).

Numerical abundance. Of the 22 species prevalent in terms of percentage of cover, seven were assessed by counting the number of individuals per panel: *Balanus amphitrite*, *B. balanoides*, *B. crenatus*, *B. eburneus*, *B. improvisus*, *Balanus* juveniles, and *Mytilus edulis* (Table 3); these organisms occur as individuals, and are most likely to influence woodborer attack. Generally, numerical abundance data support conclusions drawn from percentage cover, and demonstrate similar distributions, e.g., *Balanus crenatus* was the most abundant fouling organism, *B. improvisus* was more abundant during 2-unit operation than 3-unit operation, and was most abundant at ES, and *B. balanoides* was found only during the Feb-Aug period during 3-unit operation. In some cases, general patterns can have a single probable cause. For example, the lower abundances of juvenile *Balanus* in the Aug-Feb 'after' period, and the higher abundances in the Nov-May period are attributable to a slightly later set during this first year of 3-unit operation. If these juveniles were primarily *B. crenatus*, it would explain the generally lower densities for *B. crenatus* during the Nov-May 'after' period (i.e., individuals, settling late, were too small to be identified in May).

Wood-boring Species

Numerical abundance. Most of the wood decomposition (both naturally-occurring and in man-made structures, e.g., docks and wooden lobster pots) that occurs in local waters is the result of tunneling and feeding by shipworms, *Teredo* spp. Therefore, one measure of the intensity of potential wood-loss is the numerical abundance of teredinids. Counts of the native species of shipworm, *Teredo navalis*, were highest in panels exposed from May to November (Fig. 6), and ranged to a maximum of 300 per panel. This exposure period encompasses the entire settlement period (roughly July-September, Graves 1928; Hillman et al. 1985), and densities were higher than in Aug-Feb or Feb-Aug exposure periods, which included only part of the settlement season. Settlement of *T. navalis* did not occur during the Nov-May exposure period.

Seasonal patterns of shipworm abundance are also seen in densities of *Teredo* juveniles (Fig. 7). At ambient water sites (GN, FI, WP), young shipworms (< 5 mm; too small to be identified to species) were common only in the Feb-Aug period, indicating recent settlement. At the effluent sites (EB, ES), *Teredo* juveniles were found in each exposure period; however, these were presumably young *Teredo bartschi*, a non-native shipworm with an extended reproductive season. Adult *T. bartschi* have occurred in the MNPS effluent since 1975, and were particularly abundant (100-150 per panel) in Aug-Feb and May-Nov exposure periods (Fig. 8).

Comparisons of abundance during 2 -unit and 3-unit operation, for each category of woodborers, are presented in Table 4. Of particular interest are the increased densities of *T. bartschi* at the effluent sites, and the increased densities of *T. navalis* during the May-Nov exposure periods at WP and FI (the sites most likely to be influenced by the 3-unit plume). Densities of the wood-boring crustaceans, *Limnoria* spp. and *Chelura terebrans*, although variable in time and space, show little direct relationship to operational history or to levels of wood-loss. For example, densities of *Limnoria* and *Chelura* at WP decreased during 3-unit operation, when wood-loss increased, and densities of *Limnoria* at GN were high during the Nov-May exposure period, when wood-loss was negligible.

Percentage of wood-loss. The amount of wood lost from panels is closely related to the numerical abundance of shipworms. Wood-loss varied

TABLE 3. Average density per panel (30.6 in^2) for barnacles and mussels before (B) and after (A) three-unit operation at MNPS. Means with *'s indicate a significant difference exists between B and A (Mann-Whitney U-test, $p < 0.05$).

TAXON	SITE	EXPOSURE PERIOD							
		Aug - Feb		Nov - May		Feb - Aug		May - Nov	
		B	A	B	A	B	A	B	A
Balanus amphitrite	EB	0	1	0	0	0.2	0.5	0	1
	ES	11	0.5	0	0	1	0.4	0	0.3
	BP	1	0.2	0	0	--	1	--	1
	GN	1	0.2	0	0	12	0	0	0
	FI	0	0	0	0	3	0	0.1	0
	WP	9	0.3	1	0	15	0.2	0.1	0
Balanus crenatus	EB	18	1	148	71	0	1	0	0
	ES	7	0	32	21	0	0.1	0	1
	BP	0	0	280	71	--	266	--	0
	GN	0.1	0	236	136	101	69	1	0
	FI	3	0	435	768*	13	53	0.4	0
	WP	0.1	0.0	111	170	73	272	0	0
Balanus eburneus	EB	0	2	0	0	9	2*	10	10
	ES	8	1	0	0	8	9	19	3
	BP	0	0.6	0	0	--	8	--	6
	GN	0	0	0	0	3	0.1*	5	0
	FI	0	0	0	0	0.5	0.2	0.4	0.2
	WP	1	0	0	0	26	0	8	0
Balanus improvisus	EB	0.3	2*	0	3	10	6	1	15
	ES	239	4*	16	3	66	11*	64	13
	BP	2	1	0	0	--	10	--	4
	GN	1	0.5	0	0	6	1	3	0
	FI	7	7	0.2	0.3	1	0.4	0	6
	WP	32	1*	0.04	0.2	23	0.1*	4	0

TABLE 3. (cont'd)

TAXA	SITE	EXPOSURE PERIOD							
		Aug - Feb		Nov - May		Feb - Aug		May - Nov	
		B	A	B	A	B	A	B	A
Balanus balanoides	EB	0	0	0	0	0	0	0	0
	ES	0	0	0	0	0	0.1	0	0
	BP	0	0	0	0	0	450	0	0
	GN	0	0	0	0	0	50	0	0
	FI	0	0	0	0	0	386	0	0
	WP	0	0	0	0	0	4	0	0
Balanus juveniles	EB	12	0.3*	3	122*	211	77	0.2	30*
	ES	56	0.1*	8	14	60	41*	109	5
	BP	0.6	0.2	820	2546*	--	48	--	0
	GN	96	20*	722	2237*	45	23*	19	0
	FI	86	107	761	762	9	16	10	2
	WP	29	2*	561	2060*	308	70*	11	0
Mytilus edulis	EB	0	12	91	159*	0	0	0	0
	ES	169	20	122	318	0	0	0	0
	BP	0	0	22	3	--	2	0	0
	GN	4	0	3	0.3	22	0.1	0	0
	FI	1	0	7	33	0.3	1	0	0
	WP	150	0.2	26	6	9	0.6	2	0

among sites, exposure periods, and years (Fig. 9). At WP, FI, BP and GN, wood-loss was greatest in the May-Nov exposure period (up to 95%) and greater at GN and WP (>60%) than at BP and FI (<40%). At the effluent sites (EB and ES), considerable wood-loss occurred in both Aug-Feb and May-Nov exposure periods during 3-unit operation. At all sites, wood-loss was low during the Feb-Aug exposure period; in the Nov-May period, wood-loss was very low at the effluent sites, and zero at the ambient sites. The disproportionately low levels of wood-loss (relative to *Teredo* abundance) in Feb-Aug are explained by shipworm size; they are young and small, i.e., recently settled. Similarly, high densities of *Teredo* juveniles in Feb-Aug have little effect on wood-loss.

Interactions Between Fouling and Wood-boring Communities

Analysis of relationships among components of the communities that develop on and in the exposure panels show that densities of shipworms are negatively correlated with the abundance of foulers. In some cases, the effect of foulers on woodborers is direct, e.g., high densities of barnacles on a panel reduce the amount of space available to settling *Teredo* larvae (Fig. 10). In

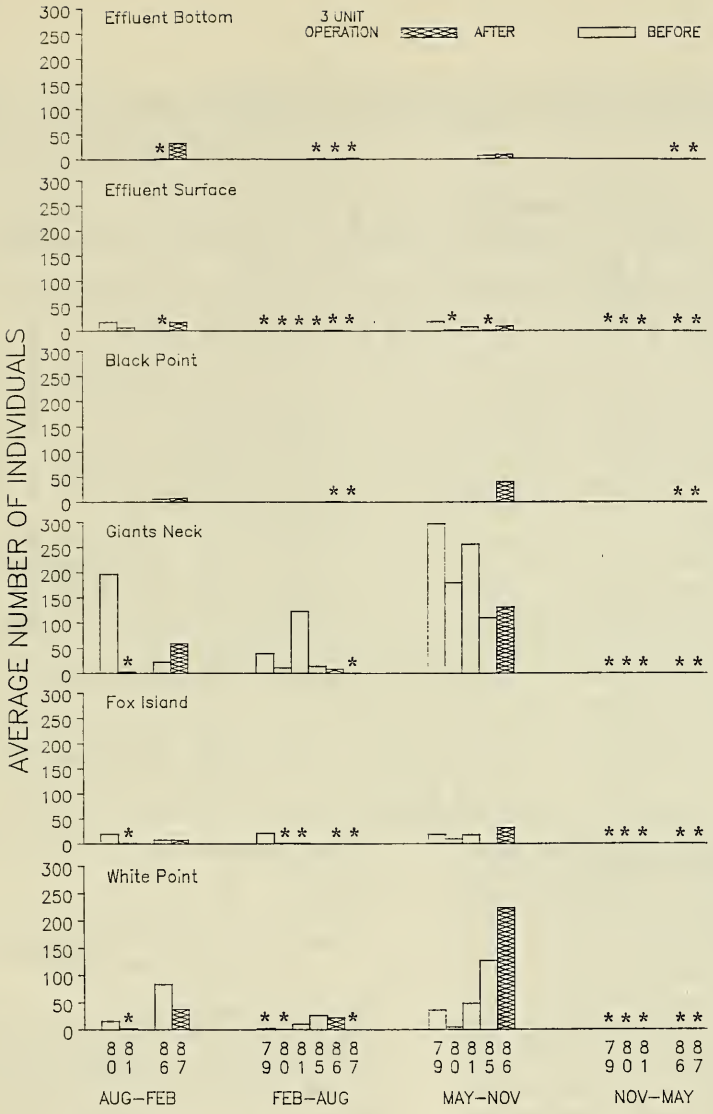

Fig. 6. Mean numerical abundance of the shipworm, *Teredo navalis*, in exposure panels collected during 1979-1987 (* = abundance < 5).

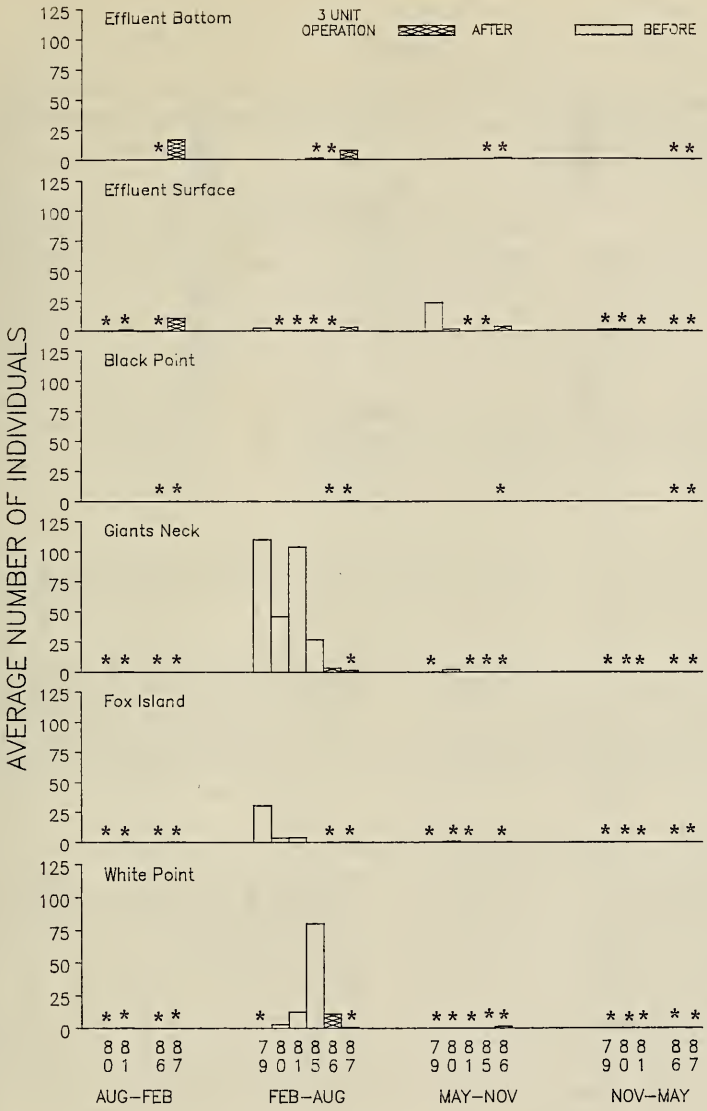

Fig. 7. Mean numerical abundance of *Teredo* juveniles in exposure panels collected during 1979-1987 (* = abundance < 5).

TABLE 4. Average density per panel (30.6 in^2) for shipworms, limnorids and chelurids before (B) and after (A) three-unit operation at MNPS. Means with *'s indicate a significant difference exists between B and A (Mann-Whitney U-test, $p < 0.05$).

		EXPOSURE PERIOD							
		Aug - Feb		Nov - May		Feb - Aug		May - Nov	
TAXON	SITE	B	A	B	A	B	A	B	A
Teredo navalis	EB	2	32*	0	0	1	1	6	8
	ES	8	17	0.04	0	0.5	1	7	9
	BP	6	8	0	0	--	0.3	--	40
	GN	74	59	0	0	47	4*	210	131
	FI	9	8	0	0	7	0	15	32*
	WP	33	37	0	0	9	11	50	223*
Teredo bartschi	EB	2	99*	0	3	3	20	8	118*
	ES	13	140*	0.1	4*	1	14*	2	72*
	BP	0	0	0	0	--	0	--	0
	GN	0	0	0	0	0	0	0	0
	FI	0	0	0	0	0	0	0	0
	WP	0	0	0	0	0	0	0	0
Teredo juveniles	EB	0	17	0	0	1	4	0	0.7
	ES	0.4	11	0.6	0.2	1	2	6	4
	BP	0	0	0	0	--	0.2	--	0
	GN	0.1	0	0	0	72	2*	0.5	0
	FI	0.6	0.2	0	0	13	0.1*	0.2	0.2
	WP	0.1	0	0	0	24	6	0	1
Limnoria spp.	EB	3	0.2	0	0.3	0.5	69*	1	0
	ES	1	0.2	1	0.2	86	2*	7	0.3
	BP	3	25	4	116*	--	142	--	216
	GN	153	26*	209	77*	567	141	335	557
	FI	26	2	0.3	0	0	0.2	0	0.3
	WP	95	37	29	66	520	185*	1610	319*
Chelura terebrans	EB	0	0	0	0	0	0	0	0
	ES	0	0	0	0	0	0	0	0
	BP	0	0	0	0	--	0.1	--	1
	GN	2	0.3	0	0	1	0	101	56
	FI	1	0	0	0	0	0.2	0	0.3
	WP	1	0.2	0	0	18	2	871	24*

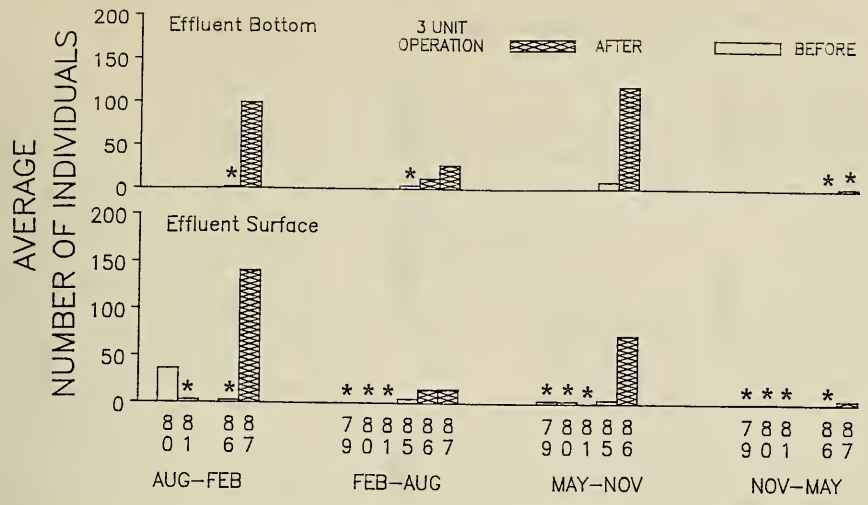

Fig. 8. Mean numerical abundance of the shipworm, *Teredo bartschi*, in exposure panels collected during 1979-1987 (* = abundance < 5).

other cases, effect is more indirect; *Limnoria*, even at high densities, does not occupy a substantial area of the panel, but its feeding and excavating activities alter panel surface characteristics and reduce shipworm recruitment (Fig. 11).

Discussion

Teredo navalis densities and percentage of wood-loss in panels were higher, in the May-Nov exposure period at WP and FI during 3-unit operation, than the average values during 2-unit operation. This pattern did not occur at at our reference sites. The sampling site at BP was not established until 1985, and most panels were lost during Hurricane Gloria; the data from the remaining panels do not provide a temporal trend. Values at GN, highest among sites during 2-unit operation, were lower than WP in 1986-1987. Because the increase at WP and FI represented only a single exposure period during 3-unit operation, it cannot yet be determined whether these values are the result of natural variability in a complex system, or the result of power plant operation. Continued association of higher shipworm densities and percentage wood-loss at sampling stations with elevated water temperatures would indicated a possible plant impact.

Warm water could influence the local woodborer community in several ways. Temperature tolerance studies conducted from 1982-1985 (NUSCO 1987) corroborate findings of other researchers, e.g., elevated water temperatures increase shipworm growth rates (Board 1973), as well as the fecundity and length of their breeding season (Naylor 1965). Warm water could also alter the competitive relationships between fouling species (Nair and Sarawathy 1971; Sutherland and Karlson 1977), or the distribution of a haplosporidian fungal parasite, implicated as a source of shipworm mortality (Hillman et al. 1982). Naylor (1965) reported that heated effluents could encourage breeding of non-native species in areas which received warm water species.

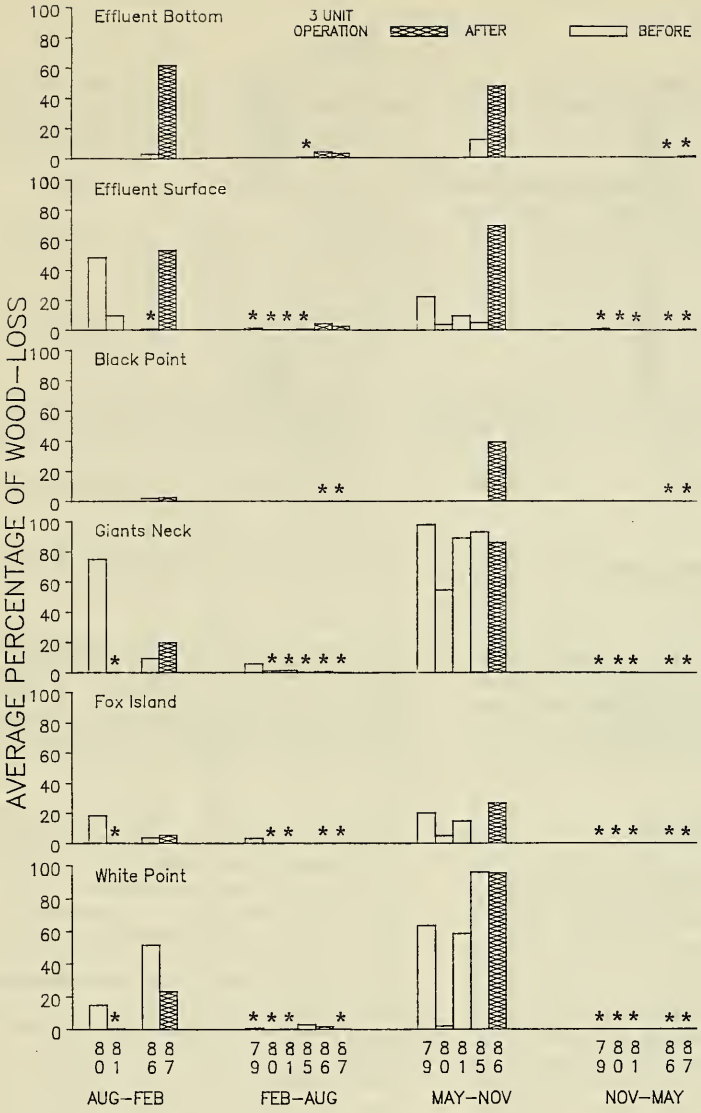

Fig. 9. Mean wood-loss from exposure panels collected during 1979-1987 (* = value < 2%).

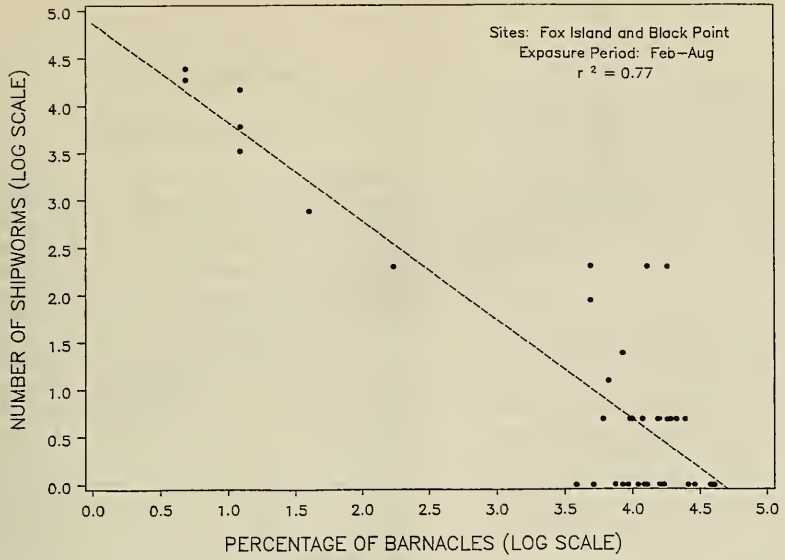

Fig. 10. The linear regression of the density of shipworms in exposure panels versus the total percentage of barnacles on panels at Fox Island and Black Point during the February to August exposure period (α = 0.0001 and r = 0.88).

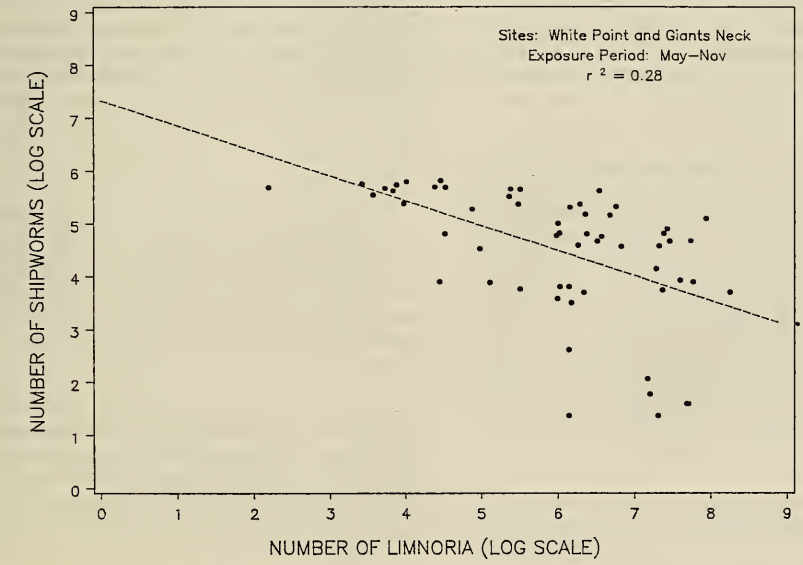

Fig. 11. The linear regression of the density of shipworms in exposure panels versus the density of limnorid isopods at White Point and Giants Neck during the May to November exposure period (α = 0.0001 and r = 0.53).

At present, the application of these mechanisms to our sample sites at WP and FI is premature; one year of 3-unit operation is insufficient to determine whether thermal incursions to these sites, of short duration, are great enough to influence the *Teredo navalis* populations. We have not identified a non-native shipworm at WP or FI, even though *Teredo bartschi* has been found in the MNPS effluent quarry since 1975.

In contrast, the woodborer populations at effluent sites were clearly affected by 3-unit operating conditions; panels at EB and ES have shown higher *Teredo bartschi* densities and greater wood-loss in May-Nov, Aug-Feb, and Feb-Aug since Unit 3 began operation. However, effluent water temperatures have not increased during 3-unit operation; average ΔT's have remained within 2-unit operation ranges. Therefore, the operational effect must be related to a factor other than temperature.

A non-thermal effect resulting from start-up of Unit 3 is increased flow and turbulence in the Millstone Quarry. *Teredo* larvae are relatively dense, and usually settle near the bottom (Graves 1928; Scheltema and Truitt 1956; Turner 1966; Nair and Saraswathy 1971). The increased turbulence may be suspending the larvae in the water column long enough to allow them to attack panels hung from the floating lab.

We have observed changes in the densities of *Teredo navalis* populations since Unit 3 began operation, and have postulated mechanisms through which these changes might have occurred. However, owing to the limited 3-unit operation database, and the high degree of natural variability typical of biological systems, at present we do not have sufficient information to assess whether the observed increases in shipworm density and wood-loss at WP and FI are related to MNPS operation. Further monitoring will increase our understanding of the system, and allow us to make that assessment.

Distribution Study

Materials and Methods

The distribution of shipworms in the MNPS effluent mixing zone was assessed, using their abundance in panels placed 100, 500, and 1000 m from the Millstone Quarry cuts (Fig. 1). At each location, five panels were attached to each of three modified lobster pots, deployed on the bottom in trawl lines (Fig. 12). Panels were first set out in May 1985. In November 1985, three panels from each pot were collected, and replaced with fresh panels (the remaining two panels in each pot served as a source community for overwintering shipworms and larvae). In May 1986, all panels were collected, and replaced with new panels. Based on the severe wood-loss seen in panels collected in November 1985, sample design was modified to provide a 5-month exposure period (May-Oct), including the time of maximum settlement and growth, and a 7-month exposure period (Oct-May), comprising months of low infestation. The trawl-line placed at 100 m in May 1986 proved impossible to maintain; people fishing in the area of the discharge frequently moved the pots or cut the buoy lines. Therefore, data from 100 m during the May-Oct 1986 exposure period are excluded from this report. Beginning in October 1986, pots at 100 m were unbuoyed, deployed and collected individually by divers.

Six of the nine panels collected from each distance in October (or November of 1985) were each cut into six segments (Fig. 12). A different section of each panel was examined; all shipworms found were removed and identified. Woodborer abundance was determined as a composite total for each distance.

Shipworm attack was minimal in panels collected in May; to quantify infestation, all panels were examined by means of X-ray photography, using the techniques described in the previous section. If shipworms were present, they were removed and identified.

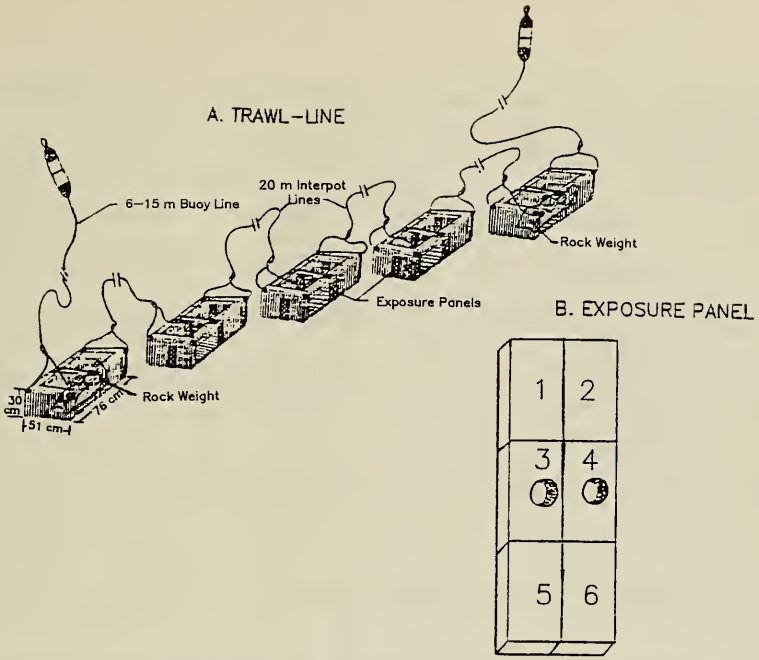

Fig. 12. Diagram of an exposure panel trawl-line used to sample the distribution of shipworms in relation to the effluent discharge point at the Millstone Nuclear Power Station (A. trawl-line of five lobster pots with the locations of the 15 pine panels; B. pine panel showing the sections for subsampling).

Results

In the four exposure periods sampled to date, 2712 shipworms have been removed and identified, excluding data from the 100 m panels in May-Oct 1986. Virtually all were from the May-Oct/Nov exposure period; four *Teredo navalis* were found in panels collected in May 1987 (Table 5). Most of the shipworms have been identified as *T. navalis*. Fourteen individuals (0.5%) were *T. bartschi*, all from 100 m panels in Nov 1985.

A trend of decreased *Teredo navalis* abundance with increased distance from the quarry cuts has been observed in the past two years (Table 5; Fig. 13). Our data from 500 m (654 shipworms) and 1000 m (525 shipworms) support conclusions drawn last year (NUSCO 1987). Temperature data, collected at 100, 500, and 1000 m sites in March 1988 (3-unit operation), are presented in Figure 14. Preliminary data show that water temperatures at the 100 m site varied with tidal stage; on a flooding tide, ambient temperatures occurred for 3-4 hours per tidal cycle, and elevated temperatures (8 °C ΔT), occurred for the remaining 8-9 hours per cycle. A temperature gradient was not seen between 500 and 1000 m, at least during early spring. Temperatures at both sites were similar to those at the intakes (i.e., ambient) and showed the same 1 °C tidal fluctuation.

Discussion

Teredo bartschi have not been found in the effluent mixing zone since Unit 3 began operation. However, our sampling gear at 100 m was removed

TABLE 5. Distribution of shipworms in relation to the effluent discharge point at the Millstone Nuclear Power Station.

Distance	Species	TOTAL NUMBER PER PANEL			
		May-Nov 1985	Nov-May 1986	May-Oct 1986	Oct-May 1987
100 m	*Teredo navalis*	601	0	---[a]	3
	Teredo bartschi	14	0	---	0
500 m	*Teredo navalis*	526	0	654	1
	Teredo bartschi	0	0	0	0
1000 m	*Teredo navalis*	388	0	525	0
	Teredo bartschi	0	0	0	0

[a]Data omitted because the pots had been moved from the sample location.

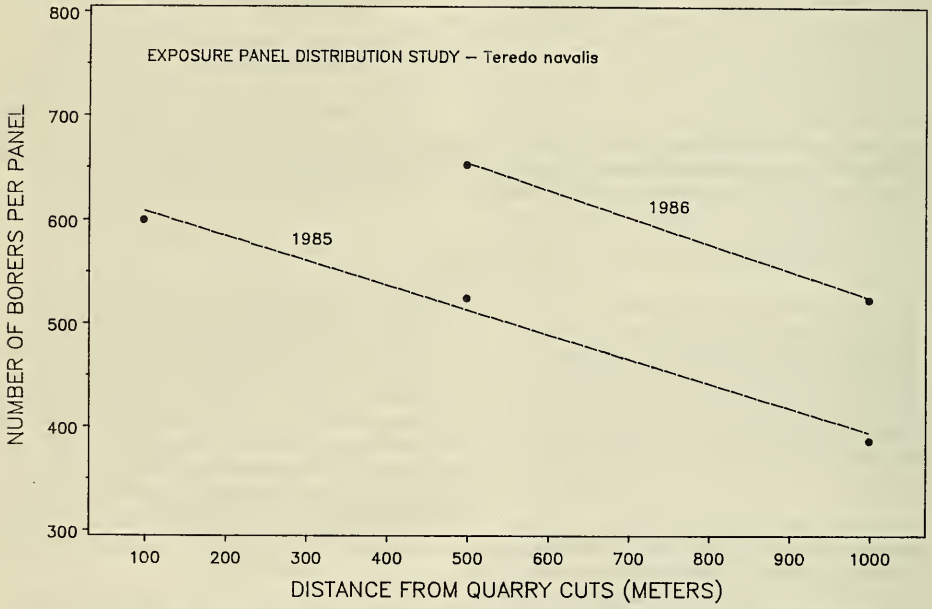

Fig. 13. The density of shipworms, *Teredo navalis*, in panels placed 100, 500 and 1000 m from the effluent discharge at the Millstone Nuclear Power Station.

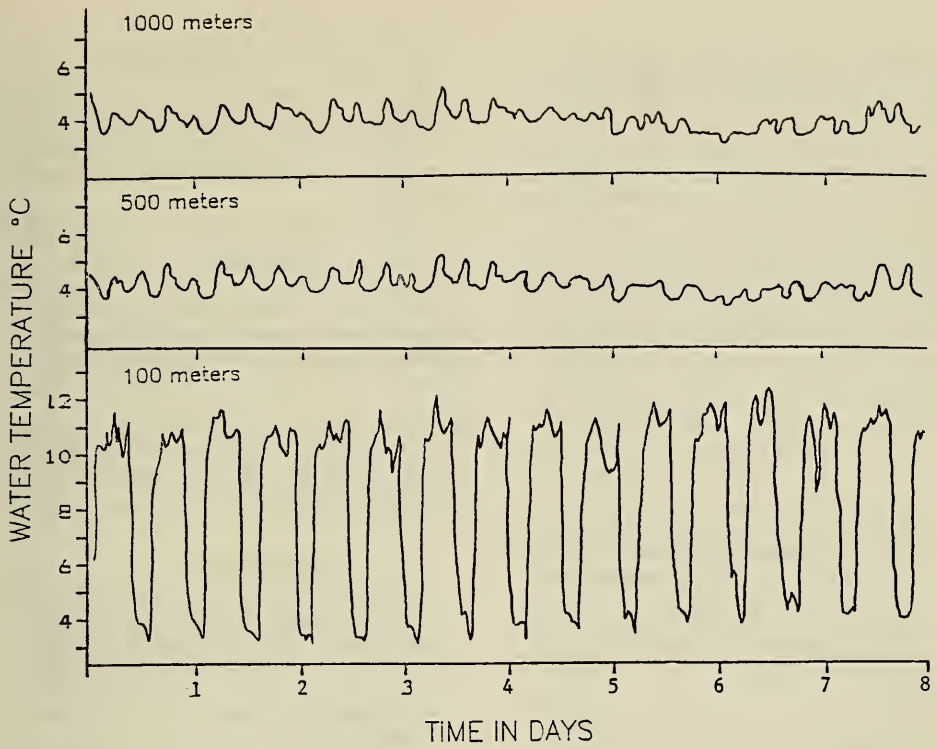

Fig. 14. Seawater temperatures on the bottom (5-11 m) at 100, 500 and 1000 m during 3-unit operation at the Millstone Nuclear Power Station. Temperature data from 100 m were collected from March 3 to March 12, 1988, while those from 500 and 1000 m were collected from March 16 to March 25, 1988.

from its designated site during the May-Oct 1986 exposure period. Based on information collected during 2-unit operation, this was the distance/period most likely to support a population of the non-native shipworm; in November 1985, we identified 14 *T. bartschi* in panels at 100 m. Therefore, the relative distribution of *T. bartschi* at 100 m during 3-unit operation will not be known until the October 1987 panels are processed. However, it is known that under 3-unit operating conditions, they have not extended their distribution to 500 or 1000 m, even though *T. navalis* settlement was high.

The continued trend of decreasing *T. navalis* abundance with increasing distance from the quarry appears to be a response to an environmental gradient. Among the possible variables are water depth, water flow, and water temperature (surface and bottom). Such a gradient would not have to persist year-round, as long as it existed during the period of shipworm settlement (June through October).

Regardless of other environmental factors that might be influencing shipworm abundance, the thermal incursions at 100 m provided an extended settlement season for *Teredo navalis*. Enhanced settlement and growth were demonstrated for shipworms grown in a mixture of Effluent and Jordan Cove water (NUSCO, unpublished data). Imai et al. (1950) noted that boring activity of larvae does not begin until water temperature reaches 14 °C. This occurs in early June at ambient sites, but given an 8 °C ΔT, it could occur in May at 100 m from the cuts. Therefore, increased densities of *T. navalis* near MNPS discharges would be expected, because seawater temperatures would enhance settlement, growth and survival.

Summary

1. The fouling community on exposure panels has shown no clear response to 3-unit operation. The assemblages continue to be diverse, and the abundance and distribution of the component species remain patchy. Throughout the study, there has been a negative correlation between fouling cover and shipworm recruitment.

2. There has been an increase in density of shipworms, *Teredo navalis*, and an increase in the amount of wood lost at the WP and FI sites during the first May-Nov exposure period of Unit 3 operation. At a reference site, GN, shipworm density decreased.

3. Higher densities of shipworms and increased wood-loss have occurred in panels in the undiluted effluent (EB and ES) during 3-unit operation, resulting from increased attack by *Teredo bartschi*, a non-native shipworm. These increases are attributed to the opportunistic life history of *T. bartschi*, but altered water circulation patterns in the effluent quarry may also expose the panels to more larvae.

4. Panels placed at 100, 500, and 1000 m from the quarry cuts continued to show increased recruitment of *T. navalis* at panels closer to the discharge. *Teredo bartschi*, which had been found in 100 m panels during 2-unit operation, was not sampled during initial 3-unit operation, because the May-Oct 100 m panels were dragged off-station by fishermen.

Conclusions

Since Unit 3 began operation, increased shipworm abundance and increased wood-loss were observed at sites in the MNPS effluent, and during one exposure period, at White Point and Fox Island, which were potentially exposed to the 3-unit thermal plume. Further monitoring will be required to determine whether these changes are related to 3-unit operation, or are expressions of natural variability.

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Fish Ecology Studies

Introduction

Fish are an important marine resource in Connecticut and millions of dollars in annual revenues are generated by the fishing industry in Long Island Sound (LIS) (Sampson 1981; Blake and Smith 1984). Commercially and recreationally important fishes are abundant in the area around Millstone Nuclear Power Station (MNPS) along with important forage species that contribute to ecosystem productivity. Some species inhabit the area seasonally for feeding, spawning, or nursery activities while others are year-round residents.

The operation of MNPS could affect fish assemblages in the area by increasing mortality rates and altering spatial distribution. Adult and juvenile fish may be removed from populations by impingement on the intake screens. Fish eggs and larvae may be removed through entrainment with the condenser cooling water. The effects of increased mortality rates on the abundance of these populations can differ depending upon the size, life span, and age structure of the affected population and on the existence of compensatory mechanisms. Spatial distributions of local fish populations may change in response to alterations in the thermal or chemical regime of the effluent or modifications to the physical habitat. Water temperature increases can attract or exclude fish from areas affected by the thermal plume of MNPS. Physical alterations caused by bottom scouring or dredging could also affect the spatial distribution of fish.

To determine if the operation of MNPS has impacted the local fish assemblages, monitoring studies have been established. The objectives of these monitoring programs are:

1. Describe the occurrence and abundance of fish in the Millstone area.
2. Identify spatial and temporal patterns of fish assemblages and establish the extent and direction of natural changes in these assemblages.
3. Evaluate whether observed changes are the result of MNPS operation, and if so, the significance of these changes, with particular emphasis on the period since Unit 3 began operating.

To meet these objectives, four sampling programs have been established to collect data on the available life history stages of those fishes susceptible to impact. These programs are the demersal trawl; shore-zone seine; ichthyoplankton, including entrainment sampling; and impingement. In this report, the life history and population characteristics of potentially impacted species are presented and evaluated to determine if MNPS has had any detrimental effects on them. Although Unit 3 did not start producing commercial power until April 23, 1986, variable numbers of condenser cooling water pumps were operated starting in November 1985. For species potentially impacted by entrainment or impingement, all of 1986 will be considered as a three-unit operational period.

The Fish Ecology section of the two-unit summary report (NUSCO 1987b) emphasized time-series analyses to describe the natural fluctuations of potentially impacted species. These time-series models represent a baseline that can be used with intervention analysis (Madenjian et al. 1986) to assess three-unit operations. But at this time, with less than 2 years of data since the start-up of Unit 3, there are insufficient data to apply intervention analyses. Therefore, in this report more conventional indices of abundance will be used for assessment.

Material and Methods

Data used for this report are from the period of January 1976 through May 1987. A reporting year included data collected from June of one year through May of the following year; thus, the report year 1986-87 included data from June 1986 through May 1987. A complete history of fish ecology programs was presented in a two-unit summary report (NUSCO 1987b) using a calender year (January through December). Prior to the summary report, the reporting period was October through September. This report period was not based on biological considerations, but on the timing of report requirements to regulatory agencies. Many of our analyses used the seasonal period of occurrence of a species (i.e., the period when 95% of the cumulative abundance was observed) and in some cases the seasonal abundance transcended the arbitrary reporting periods of October through September or the calender year. Considering the seasonal occurrence of our abundant species, June was the best transitional period. By the end of May the early life history stages of the winter-spawning species were no longer susceptible to entrainment and summer spawners were not yet abundant. Because of occasional overlap in the occurrence of a species during this May-June transitional period, species-specific analyses are based on the period of occurrence of each species and not absolutely constrained to June 1 as the starting point. If a life history stage occurred during the June-December period, only the 1986 season of three-unit operation is given in this report, whereas, if it occurred in the January-May period, the 1986 and 1987 seasons of three-unit operation are reported. The materials and methods presented are for 1985-86 and 1986-87 reporting periods, except for impingement monitoring, which was discontinued at Unit 2 on December 11, 1987. Impingement data are summarized through 1987 using a calender reporting year.

Trawl program

Demersal fishes were collected using a 9.1-m otter trawl with a 0.6-cm codend liner. Triplicate tows were made biweekly at six stations: Niantic River (NR), Jordan Cove (JC), Twotree (TT), Bartlett Reef (BR), Intake (IN) and Niantic Bay (NB) (Fig. 1). A standard tow covered 0.69 km and this distance was measured using radar. The total length of up to 50 randomly selected individuals of each species per station was measured to the nearest millimeter. Catch was expressed as the number per tow. Data are reported from June 1976 through May 1987.

Seine program

Shore-zone fishes were sampled using a 9.1 x 1.2-m knotless nylon seine net of 0.6-cm mesh. Triplicate 30-m tows were made parallel to the shoreline at White Point (WP), Jordan Cove (JC) and Giants Neck (GN), monthly from November through March and biweekly April through October (Fig. 1). Collections were made during the period of 2 hours before to 1 hour after high tide and all three stations were sampled the same day. Fish in each haul were identified to the lowest possible taxon, counted, and the total length of up to 50 randomly selected individuals of each species in each replicate was measured to the nearest millimeter. Catch was expressed as the number per haul. Data are reported from June 1976 through May 1987.

Impingement program

Fish impinged on the intake screens at Unit 2 were washed at least once ever 8 hours into a 1.5 x 0.8 x 1.75-m perforated collection basket. Impingement sampling consisted of sorting specimens from all material washed from the screens during a 24-hour period. All were identified to the lowest possible taxon, counted, and the total length of up to 50 randomly selected specimens of each species was measured to the nearest millimeter. Catch was calculated as number impinged per 24-hour period. Sampling effort was stratified

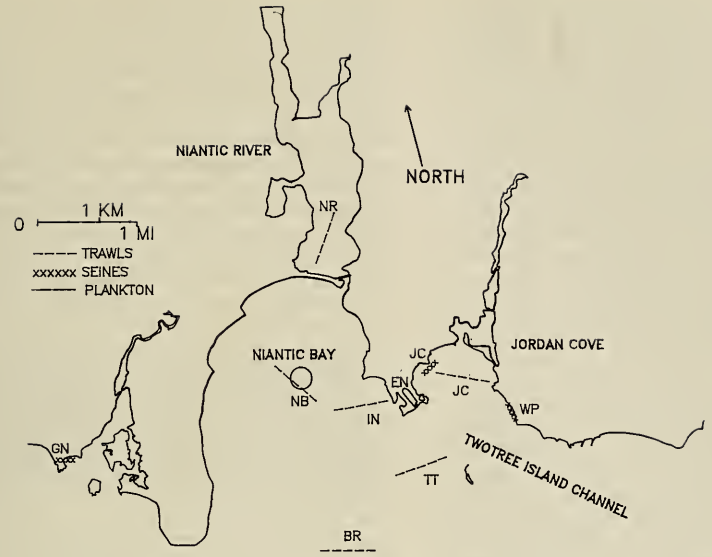

Fig. 1. Location of trawl, seine, and ichthyoplankton sampling stations.

by month, with 8 samples collected in January, 15 in February, 14 in March, 5 in April, 4 per month during May through November, and 10 in December. Data are reported from January 1976 through December 11, 1987.

Ichthyoplankton program

Weekly samples of entrained ichthyoplankton (fish eggs and larvae) were collected during 3 day and 3 nights from June through September, on 1 day and 1 night from October through February, and during 4 days and 4 nights from March through May. Sampling alternated weekly between the discharges of Units 1 and 2 (station EN) when plant operations permitted. A 1.0 x 3.6-m conical plankton net with 333-µm mesh was deployed with a gantry system. Four General Oceanic flowmeters (Model 2030) were positioned in the mouth of the net to account for horizontal and vertical flow variations. Sample volume (about 400 m^3) was determined by averaging the four volume estimates from the flowmeters.

Larvae were collected at station NB located in mid-Niantic Bay (Fig. 1). Weekly 2 day and 2 night samples were taken from June through August and April through May, and biweekly 1 day and 1 night sample taken from September through March. Paired 0.61 x 3.3-m conical plankton nets, mounted on a bongo frame, were used to take stepwise oblique tows. Sampling duration was 5 minutes each at surface, mid, and bottom depths. Sample volumes were measured using one General Oceanics flowmeter in each net and approximately 300 m^3 of seawater were filtered

for each sample. Net mesh size was 333 μm, except for a period from mid-February through March, when 202-μm mesh nets were used to reduce the extrusion of yolk-sac winter flounder larvae (see Winter Flounder Studies section).

Plankton samples were split using a NOAA-Bourne splitter (Botelho and Donnelly 1978) and sorted for ichthyoplankton using dissecting microscopes. Successive splits were completely sorted until at least 50 larvae and 50 eggs (for samples processed for eggs) were found, or until one-half of the sample was examined. Samples sorted for larvae included all those from EN collected during January through May and July through December, one day and one night sample collected per week during June, and all NB samples. Three day and three night EN samples collected in April through September were sorted for fish eggs. Fish eggs and larvae were identified to the lowest practical taxon. Cunner and tautog eggs were differentiated from a weekly composite sample of their eggs using the criterion of bimodality of egg diameters (Williams 1967). Ichthyoplankton density was expressed as number per 500 m^3. Included in this report are ichthyoplankton data through May 1987, starting with egg collections at EN in May 1979; larval collections at EN in January 1976 and at NB in January 1979.

Data analyses

To assess impacts it was necessary to identify potentially affected species, document their spatial distribution, and describe the natural temporal fluctuations of their life history stages collected near Millstone. The selection of potentially affected species was based on their prevalence in entrainment or impingement samples or their abundance in the shore-zone area of Jordan Cove, an area which may be impacted by the thermal plume. Indices to describe temporal and spatial abundance for all life history stages of fishes must be selected based on the knowledge of the underlaying assumptions of each index. Failure of the data to conform to these assumptions may reduce the precision of the estimates or, worse, provide invalid results. Since fisheries data typically have numerous zero values and follows a lognormal distribution, the δ-mean (Pennington 1983, 1986) was used as the index of abundance of various life history stages of selected species. A detailed description and evaluation of this statistic is provided in a separate section (see Delta Distribution section). The δ-mean was used as an index of abundance for juveniles and adults collected in the trawl and seine programs and for larvae that were not consistently collected during their seasonal occurrence. For species that were collected seasonally, the data used to calculate the δ-mean were restricted to the period of occurrence to reduce the number of zero values. An alternative index of abundance, used for ichthyoplankton that were collected consistently during their seasonal occurrence, was the α parameter from the Gompertz function (Draper and Smith 1981). Typically, the distribution of ichthyoplankton abundance over time is skewed, with a rapid increase to a maximum followed by a slower decline. This skewed density distribution results in a sigmoid-shaped cumulative distribution and the time of peak abundance is the time at which the inflection point occurs in the cumulative distribution. The Gompertz function was chosen to describe the cumulative distribution data because the inflection point of this function is not constrained to the central point of the sigmoid curve. The form of the Gompertz function was:

$$C_t = \alpha(\exp[-\beta e^{-\kappa t}])$$

where C_t = cumulative density at time t

α = total or asymptotic cumulative density

β = location parameter

κ = shape parameter

t = time in days

The origin of the time scale was arbitrary and for our data was set to the time of the year that the respective developmental stage generally starts to appear in ichthyoplankton samples. Least-

squares estimates of these parameters and their asymptotic 95% confidence intervals were obtained by fitting the Gompertz function to the cumulative abundance data (based on the weekly geometric means) using nonlinear regression methods (SAS Institute Inc. 1985). The α parameter was used as an index to compare annual abundances and the time of peak abundance was estimated as the date t_i corresponding to the inflection point of the function defined by its parameters β and κ as:

$$t_i = \frac{(\log_e \beta)}{\kappa}$$

The presence of compensatory mortality during the early life history stages would help mitigate the loss of entrained eggs and larvae. When abundance estimates of both eggs and larvae were available, density-dependent mortality was investigated with the following relationship (Ricker 1975):

$$\log_e\left(\frac{L}{E}\right) = \alpha + \beta E$$

where L = larval abundance estimate
E = egg abundance estimate
α = intercept
β = index of density-dependent mortality

If the slope (β) is positive the density-dependent mortality is depensatory and if negative it is compensatory.

Annual entrainment estimates were calculated for dominant ichthyoplankton species entrained. These estimates were obtained by multiplying the median density at EN during the period when 95% of the annual cumulative abundance occurred times the total volume of water passed through MNPS during the same period. A nonparametric method (Snedecor and Cochran 1967) was used to construct 95% confidence intervals around each median density and corresponding entrainment estimate.

Monthly impingement estimates were based on the extrapolation of actual counts using a volumetric ratio. The daily cooling water volume was calculated based on 15-minute flow rates from 0800 to 0745, the time corresponding to the actual impingement period. Within each month, an estimate for every day not sampled was calculated by multiplying the average impingement density (number of fish per m^3 of cooling water) based on the days sampled in that month times the volume of cooling water on each day not sampled. All of these daily estimates were then added to the sum of the actual sample counts to arrive at the monthly totals for each species. Annual impingement estimates were calculated by summing the monthly estimates.

As stated previously, seine sampling effort was stratified by season and impingement sampling was stratified by month. Therefore, whenever appropriate, the length-frequency data were weighted to account for unequal effort during the year. Because seine sampling effort from April through October was twice that during the remainder of the year, data collected from November through March were weighted by a factor of two. For impingement collections, monthly weight factors of 4 (January), 2 (February and March), 6 (April), 7 (May through November), and 3 (December) were used to standardize the effort.

Data on the annual abundance of fishes in LIS and adjacent areas were examined to determine if observed changes in the Millstone area were localized or evident over a larger area. Trawl and ichthyoplankton data were available from monitoring studies at the Shoreham Nuclear Power Station (SNPS) and summarized for 1977-82 (Geomet Tech. 1983) and 1983-1986 (EA Eng., Sci., and Tech. 1987). SNPS is located on the southern shore of LIS almost directly south of New Haven, CT. The available trawl data were converted to annual catch-per-unit-effort for day collections. The ichthyoplankton data were summarized in the reports for 1977-82 as the annual sum of the mean densities (1000 m^3) per sampling trip and for 1983-86 as the annual sum of the monthly mean densities. Because the 1977-82

period contained some months when two sampling trips were made, a direct comparison of 1977-82 to 1983-86 data cannot be made, but the information should be sufficient to determine long-term trends. For the potentially impacted species in the Millstone area, sufficient data were available from the SNPS data base for comparisons with egg abundance of anchovies, cunner, and tautog; larval abundance of sand lance, anchovies, cunner, and tautog; and trawl catches of anchovies, cunner, and tautog. Additional trawl data were available from the National Marine Fisheries Service (NMFS) ground trawl survey (Grosslein 1974; Azarovitz 1981). Data were obtained from selected strata off southern Long Island, NY; Rhode Island; and southwestern Massachusetts. These data were provided by NMFS as the annual δ-mean for both spring and fall surveys. Because of limited catches of most potentially affected species, only sand lance data were sufficient for comparisons.

Results and Discussion

Over 100 fish taxa from ichthyoplankton, impingement, trawl, and seine samples have been collected in the Millstone area from 1976 through May 1987 (Appendix I). The most common were American sand lance (*Ammodytes americanus*), winter flounder (*Pseudopleuronectes americanus*), anchovies (*Anchoa mitchilli* and *A. hepsetus*), sticklebacks (*Gasterosteus aculeatus* and *G. wheatlandi*), silversides (*Menidia menidia* and *M. beryllina*), Atlantic tomcod (*Microgadus tomcod*), grubby (*Myoxocephalus aenaeus*), skates (*Raja erinacea, R. ocellata*, and *R. eglanteria*), scup (*Stenotomus chrysops*), windowpane (*Scophthalmus aquosus*), tautog (*Tautoga onitis*), and cunner (*Tautogolabrus adspersus*). These taxa were typical of fish assemblages found in LIS (Greeley 1938; Warfel and Merriman 1944; Wheatland 1956; Richards 1959; Pearcy and Richards 1962; McHugh 1972; Saila and Pratt 1973; Geomet Tech. 1983). Important recreational and commercial fishes, such as, bluefish (*Pomatomus saltatrix*) and striped bass (*Morone saxatilis*), that occurred in the Millstone area were not susceptible to our sampling gear. However, they were rare in the entrainment and impingement collections, so the potential impact of MNPS on these species is minimal. The following is a summary of the fishes collected in each sampling program to show which taxa and life history stages predominated in the Millstone area.

Trawl monitoring

In the trawl program, over 90 taxa of juvenile and adult fishes were taken at six stations in the Millstone area during the past 11 years (Appendices II and III). The demersal fishes collected in the trawl monitoring program were similar to those found in Narragansett Bay (Oviatt and Nixon 1973). Since 1976, six fish taxa comprised over 80% of the trawl catch and winter flounder accounted for over 40% of the total. The winter flounder was caught throughout the year in the Millstone area and due to its commercial and recreational importance is discussed in detail in a separate section (see Winter Flounder Studies section). The second most abundant species (15%) was the scup, which was found from June through October. Most scup were juveniles and over 40% of them were caught at NB. Anchovies, which accounted for over 8% of the trawl catch, were also found primarily at NB from August through October and were primarily young-of-the-year. Our demersal trawl does not uniformly sample anchovies, most likely because of their location in the water column, small size, and patchy distribution. Annual catches of anchovies were variable and the highest catch occurred in 1985. Windowpane and skates, both resident taxa, together accounted for an additional 13% of the catch. Both were most often found at the deeper water stations (TT and BR). Silversides were the sixth most abundant taxon caught by trawl. They were the dominant shore-zone taxon in the Millstone area and were caught in trawls during the the winter, primarily from October through February.

Annual δ-mean catches (all stations combined) were calculated to examine year to year variation for the six dominant taxa in the trawl monitoring program (Table 1). For taxa that occur seasonally,

TABLE 1. The seasonal[a] δ-mean (CPUE) of the abundant fish taxa caught in trawls during each report period (June-May).

Taxon	76-77	77-78	78-79	79-80	80-81	81-82	82-83	83-84	84-85	85-86	86-87
Pseudopleuronectes americanus	16.6	13.5	16.7	26.8	32.6	24.1	41.8	27.7	29.5	22.0	19.8
Stenotomus chrysops	10.6	19.8	13.3	18.5	17.0	20.4	27.5	26.6	22.3	13.6	30.6
Anchoa spp.	11.1	3.3	39.3	0.1	0.1	4.0	0.2	0.4	0.7	113.8	57.38
Scophthalmus aquosus	2.9	2.4	1.8	2.9	3.5	2.9	6.7	5.0	4.4	4.7	3.8
Raja spp.	1.4	1.2	0.8	0.8	2.0	1.4	6.1	5.3	3.1	8.5	4.5
Menidia spp.	16.2	9.7	2.8	6.2	6.5	1.8	1.5	2.1	0.5	1.9	17.8

[a] Data seasonally restricted to June-October for *Stenotomus chrysops*, to August-October for *Anchoa* spp. , to October-February for *Menidia* spp. , and remaining taxa year-round (June-May)

data for this analysis were limited to their season of occurrence: June through October for scup, August through October for anchovies and October through February for silversides. The δ-mean catch for all of the dominant species has fluctuated and during three-unit operation the catches were within or above historical ranges with some of the highest abundances for scup, anchovies, and silversides.

Seine monitoring

Approximately 40 different taxa have been caught by seine during the past 11 years of monitoring (Appendices IV and V). Silversides dominated the shore-zone catches and accounted for over 80% of the total. About 80% of the total seine catch was collected at JC. This station is a productive nursery area, and hundreds of juvenile silversides are routinely caught at this site during the summer months (June through September). Because silversides dominated all the annual catches, total catches were largely a function of silverside catches. Total catches for all shore-zone taxa were highest during the 1976-77 and 1977-78 report periods and were dominated by juvenile silversides at JC (NUSCO 1987b). Because the silversides dominated the shore-zone area of Jordan Cove, which may be thermally impacted by the condenser cooling water discharge, it was selected as a potentially impacted taxon and is discussed in further detail later.

Impingement monitoring

Impingement has been monitored at Millstone Unit 2 since it began operating in September 1975. The objective of the monitoring program was to quantify total annual species-specific loss due to impingement. Because impingement losses have been well-documented and measures to mitigate impingement losses have been investigated, a request was submitted to the Connecticut DEP in July 1987 to discontinue impingement monitoring at Unit 2 (NUSCO 1987a). The DEP accepted our request and sampling was discontinued on December 11, 1987.

Annual impingement estimates were calculated from January 1, 1976 through December 11, 1987. Over 100 fish and invertebrate taxa were impinged during the past 12 years (Tables 2 and 3). Sand lance accounted for over 60% of the total because an estimated 480,000 were impinged during the week of July 18, 1984. Impingement of sand lance during that week accounted for over 98% of the 12-year total for that species. The sand lance is a schooling species (Leim and Scott 1966) and a large school encountered the intake structure. Excluding sand lance, six fish taxa dominated the collections: winter flounder, anchovies, grubby, silversides, sticklebacks, and Atlantic tomcod (Table 4). These taxa were selected as potentially impacted species and discussed in further detail later, except for winter flounder (see Winter Flounder Studies section).

TABLE 2. Annual impingement estimates for fish taxa impinged at MNPS Unit 2 from January 1, 1976 through December 11, 1987.

Taxon	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	Total
Ammodytes spp.	46	20	239	59	168	223	81	161	485411	73	42	8	486531
Pseudopleuronectes americanus	2783	4604	3184	10077	3576	6207	2735	6213	2542	2769	1049	624	46363
Myoxocephalus aenaeus	1027	1299	3980	1721	9167	3262	2671	7023	2359	4621	1427	647	39204
Anchoa spp.	848	177	774	2508	4073	3722	4085	12726	4200	342	38	12	33505
Menidia spp.	853	503	2292	3319	8676	2769	800	3759	1042	1484	511	136	26144
Microgadus tomcod	45	86	1956	768	1213	2809	10302	2264	4938	1130	8	206	25725
Gasterosteus wheatlandi	.	.	.	.	.	580	1090	11691	702	21	1799	1822	17705
Gasterosteus spp.	1533	3609	3480	2241	6710	.	.	.	.	.	.	.	17573
Gasterosteus aculeatus	.	.	.	.	.	5883	1188	4638	1055	859	921	572	15116
Syngnathus fuscus	559	260	875	425	766	1417	557	3503	1467	460	858	748	11895
Peprilus triacanthus	114	122	233	1091	781	1416	2414	465	1455	1337	1406	946	11780
Tautogolabrus adspersus	357	598	1399	1656	751	883	1787	694	1188	466	57	642	10478
Merluccius bilinearis	586	304	282	361	1659	277	422	998	133	106	44	41	5213
Scophthalmus aquosus	434	188	243	503	570	367	354	1241	569	174	292	224	5159
Morone americana	136	260	458	230	489	491	1340	476	375	48	19	2	4324
Tautoga onitis	464	98	731	578	106	434	397	168	664	122	96	241	4099
Cyclopterus lumpus	26	265	209	248	689	329	9	499	120	1010	128	204	3736
Raja spp.	292	165	133	170	231	464	274	626	275	99	285	268	3282
Osmerus mordax	282	204	390	62	101	283	184	897	71	99	105	60	2738
Paralichthys dentatus	230	17	59	7	27	261	88	72	646	29	377	469	2282
Brevoortia tyrannus	177	50	62	135	154	101	247	311	167	242	55	56	1757
Prionotus spp.	364	112	63	49	61	242	147	86	49	72	142	71	1458
Cynoscion regalis	26	568	70	4	7	466	40	38	34	14	8	54	1329
Alosa pseudoharengus	48	274	26	92	118	128	203	192	79	59	32	21	1272
Alosa aestivalis	86	125	88	140	94	121	63	234	91	51	42	2	1137
Sphoeroides maculatus	165	4	17	49	12	80	126	166	174	86	81	44	1004
Liparis spp.	6	208	86	11	25	371	19	155	39	66	0	5	991
Anguilla rostrata	60	25	56	84	73	66	207	104	60	48	10	59	852
Stenotomus chrysops	114	76	19	87	35	78	115	95	53	105	23	6	806
Opsanus tau	69	27	77	96	49	123	55	67	98	28	23	75	787
Pholis gunnellus	48	28	39	86	28	88	42	121	49	12	24	35	600
Pomatomus saltatrix	23	44	9	47	27	81	40	108	110	46	34	6	575
Pollachius virens	5	6	2	2	71	55	41	41	253	0	37	0	513
Trinectes maculatus	20	6	14	53	35	21	75	29	194	21	21	12	501
Fundulus spp.	12	16	91	14	75	99	33	13	20	8	0	0	381
Clupea harengus	33	114	0	5	2	35	9	16	12	12	5	98	341
Urophycis chuss	3	17	0	80	19	42	26	41	71	13	0	6	318
Hemitripterus americanus	9	2	5	2	25	64	51	94	22	6	12	0	292
Urophycis regia	5	0	0	3	14	12	19	187	7	0	13	0	260
Caranx hippos	5	0	2	4	2	47	91	9	21	34	8	0	223
Gadus morhua	0	0	0	0	0	10	24	2	142	7	16	0	201
Ophidion marginatum	16	0	0	10	0	0	7	4	50	6	17	49	159
Urophycis spp.	0	29	124	0	2	2	0	0	0	0	0	0	157
Centropristis striata	22	2	0	0	7	0	2	6	74	0	28	0	141
Mugil cephalus	3	4	10	4	18	5	7	17	39	4	19	0	130
Sphyraena borealis	12	4	10	0	0	25	63	0	12	0	0	0	126
Leiostomus xanthurus	12	2	83	0	0	0	2	16	0	0	8	0	123
Monacanthus hispidus	5	0	34	45	8	4	4	7	3	9	0	0	119
Etropus microstomus	2	0	0	0	0	5	4	41	20	10	22	14	118
Apeltes quadracus	2	4	2	2	31	45	12	3	2	0	6	2	111
Alosa sapidissima	12	1	0	2	33	16	6	17	16	0	0	0	103
Melanogrammus aeglefinus	0	0	4	88	3	0	0	0	0	0	0	0	95
Selene setapinnis	30	0	0	0	0	0	2	2	20	34	7	0	95
Urophycis tenuis	0	1	4	0	4	17	13	2	45	0	0	0	86
Pungitius pungitius	0	0	2	0	0	4	19	17	5	10	19	2	78
Paralichthys oblongus	16	0	4	7	4	16	2	4	0	6	0	15	74
Selene vomer	0	22	0	0	5	0	2	0	14	22	0	7	72
Scomber scombrus	0	4	0	4	0	12	46	2	0	0	0	0	68
Aluterus schoepfi	1	36	4	0	3	0	9	0	6	0	0	0	59
Caranx crysos	0	9	7	0	0	5	14	0	24	0	0	0	59

TABLE 2. Continued.

Taxon	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	Total
Alectis ciliaris	1	7	2	0	0	28	2	0	6	7	0	0	53
Mugil curema	0	0	0	0	0	10	0	3	27	8	4	0	52
Mustelis canis	2	6	18	2	0	6	4	0	0	8	6	0	52
Fistularia tabacaria	3	4	5	0	10	2	5	0	0	6	0	0	35
Lophius americanus	0	0	0	0	0	0	2	0	0	7	0	24	33
Squalus acanthias	2	0	0	0	6	0	0	21	0	0	2	2	33
Myoxocephalus spp.	1	31	0	0	0	0	0	0	0	0	0	0	32
Morone saxatilis	0	0	3	2	0	0	13	5	0	7	0	0	30
Hippocampus erectus	2	0	0	0	0	0	0	4	0	3	13	7	29
Ulvaria subbifurcata	2	1	3	2	0	7	2	0	6	4	0	0	27
Conger oceanicus	13	4	0	0	0	2	5	2	0	0	0	0	26
Myoxocephalus octodecemspinosus	0	0	0	5	5	2	4	8	0	0	0	0	24
Dactylopterus volitans	0	2	0	0	0	0	4	0	0	7	0	10	23
Myoxocephalus scorpius	0	16	6	0	0	0	0	0	0	0	0	0	22
Ophidiidae	17	0	0	0	0	0	5	0	0	0	0	0	22
Trachurus lathami	0	0	0	16	0	4	0	0	0	0	0	0	20
Chaetodon ocellatus	0	0	2	0	0	2	7	0	0	7	0	0	18
Gadidae	0	0	5	0	0	0	13	0	0	0	0	0	18
Decapterus macarellus	0	0	0	0	0	0	0	0	15	0	0	0	15
Enchelyopus cimbrius	0	0	0	0	0	0	0	0	8	0	0	6	14
Pristigenys alta	0	0	0	0	0	0	2	0	12	0	0	0	14
Cyprinodon variegatus	0	0	4	0	4	2	2	0	0	0	0	0	12
Chilomycterus schoepfi	0	0	0	0	0	0	2	0	8	0	0	0	10
Macrozoarces americanus	0	0	0	2	0	0	0	2	0	6	0	0	10
Etrumeus teres	0	2	0	5	0	0	2	0	0	0	0	0	9
Priacanthus arenatus	0	0	0	0	0	0	2	0	6	0	0	0	8
Clupeidae	0	0	0	0	0	0	0	0	3	4	0	0	7
Menticirrhus saxatilis	0	0	2	3	0	0	2	0	0	0	0	0	7
Alosa spp.	0	0	0	0	0	0	0	0	6	0	0	0	6
Hippocampus spp.	0	0	0	0	0	0	0	0	0	6	0	0	6
Priacanthus cruentatus	0	0	0	0	0	2	0	4	0	0	0	0	6
Selar crumenophthalmus	3	0	0	0	0	2	0	0	0	0	0	0	5
Seriola zonata	0	5	0	0	0	0	0	0	0	0	0	0	5
Aulostomus maculatus	3	0	0	0	0	0	0	0	0	0	0	0	3
Monocanthus spp.	0	0	0	0	0	0	0	0	3	0	0	0	3
Alosa mediocris	0	0	0	0	0	0	2	0	0	0	0	0	2
Decapterus punctatus	0	0	0	0	0	2	0	0	0	0	0	0	2
Ictalurus catus	2	0	0	0	0	0	0	0	0	0	0	0	2
Rhinoptera bonasus	0	0	0	0	0	2	0	0	0	0	0	0	2
Salmo trutta	0	0	0	2	0	0	0	0	0	0	0	0	2
Total	12077	14677	21981	27268	40822	34636	32745	60410	511387	16360	10199	8560	791122

Many researchers have found that impingement rates were directly influenced by cooling-water flow (ConEd and PASNY 1977; Lawler, Matusky and Skelly Engineers 1980, 1987). The estimated total number of fish impinged each year by MNPS was compared to annual cooling-water volume (Fig. 2). Annual impingement at Unit 2 from 1976 to 1982 appeared to be related to cooling-water flow. In 1983, cooling water flow was low while the number of fish impinged was high; Unit 2 was at full power during the winter of 1983, but was shutdown from June through November. Except for anchovies, the more abundant fishes were usually impinged in greater numbers during the winter; this accounted for the differences noted between catch and flow in 1983. In the fall of 1983, there was a noticeable reduction in daily impingement at Unit 2 after the summer removal of a cofferdam surrounding the Unit 3 intake. The cofferdam existed when Unit 2 began operating and it provided a reef-like habitat in the vicinity of the Unit 2 intake that may have attracted fish. Analyses of daily monitoring data revealed a significant ($p < 0.01$) reduction in the average number of organisms impinged at Unit 2 after the removal of the cofferdam (NUSCO

TABLE 3. Annual impingement estimates for invertebrate taxa impinged at MNPS Unit 2 from January 1, 1976 through December 11, 1987.

Taxon	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	Total
Ovalipes ocellatus	1402	2289	1831	4708	14224	13054	23194	4876	4118	2838	1552	1343	75429
Loligo pealei	5095	1257	2430	10763	11083	7895	6846	2779	14748	3298	1912	1491	69597
Cancer irroratus	457	389	442	438	560	3919	5179	4036	6680	4456	6264	2365	35185
Carcinus maenus	425	408	368	408	670	2339	1532	4311	5647	2727	2960	1571	23366
Callinectes sapidus	564	193	499	945	927	964	1120	468	1020	733	621	988	9042
Homarus americanus	663	308	261	402	392	1043	1032	458	1167	505	549	825	7605
Libinia spp.	1244	205	93	91	124	516	475	887	1484	407	689	283	6498
Neopanope texana	0	13	16	13	18	104	362	288	1496	244	373	186	3113
Limulus polyphemus	281	11	17	54	46	152	86	10	164	0	41	275	1137
Pagurus spp.	227	37	8	4	88	38	14	11	12	7	83	54	583
Squilla empusa	52	38	4	2	193	23	20	25	3	3	0	65	428
Cancer borealis	12	4	5	77	9	10	11	12	2	0	0	0	142
Argopecten irradians	0	0	0	0	0	2	2	37	38	0	0	0	79
Penaeus aztecus	0	0	0	0	2	2	45	0	0	7	7	0	63
Upogebia affinis	0	0	0	0	0	0	14	39	0	0	0	0	53
Illex illecebrosus	0	5	6	0	0	9	0	0	6	0	0	0	26
Callinectes similis	0	0	0	0	0	0	14	0	0	0	0	0	14
Lunatia heros	0	0	0	0	2	0	2	0	0	0	0	0	4
Aplysia wilcoxi	0	0	0	0	2	0	0	0	0	0	0	0	2
Rana pipens	0	0	0	0	0	0	0	2	0	0	0	0	2
Hexapanopeus angustifrons	1	0	0	0	0	0	0	0	0	0	0	0	1
Total	10423	5157	5980	17905	28340	30070	39948	18239	36585	15225	15051	9446	232369

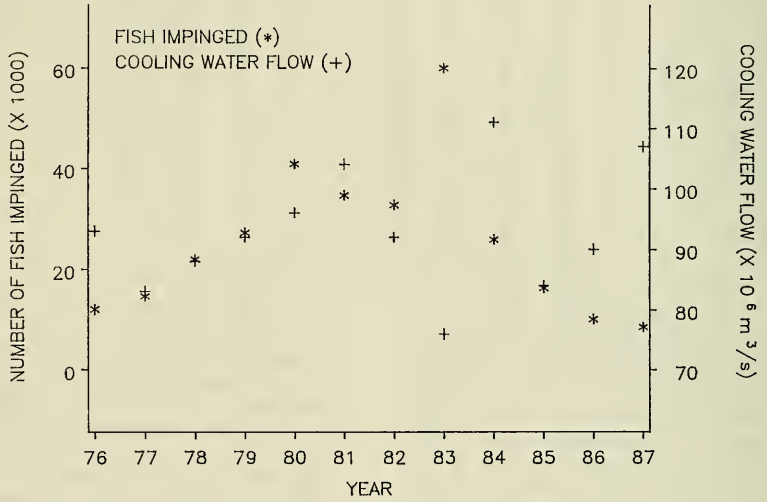

Fig. 2. Annual total impingement estimates and total condenser cooling water flows at MNPS Unit 2. The large impingement of sand lance in 1984 was excluded from that annual total.

TABLE 4. Percent contribution of the dominant taxa collected in entrainment samples at Units 1 and 2 and estimated impingement at Unit 2.

Taxon	Entrainment		Impingement
	Larvae	Eggs	
Anchoa spp.	62.7	10.5	14.5
Pseudopleuronectes americanus	10.3	0.0	16.0
Ammodytes spp.	9.1	0.0	0.3[a]
Myoxocephalus aenaeus	3.9	0.0	11.4
Pholis gunnellus	1.9	0.0	0.2
Brevoortia tyrannus	1.7	0.0	0.5
Tautogolabrus adspersus	1.7	53.4	3.6
Tautoga onitis	1.7	29.3	1.6
Syngnathus fuscus	1.0	0.0	3.2
Liparis spp.	0.9	0.0	0.3
Ulvaria subbifurcata	0.8	0.0	0.0
Scophthalmus aquosus	0.7	1.6	1.7
Peprilus triacanthus	0.7	0.0	3.1
Enchelyopus cimbrius	0.6	0.5	0.0
Gobiidae	0.3	0.0	0.0
Prionotus spp.	0.3	2.0	0.3
Myoxocephalus octodecemspinosus	0.2	0.0	0.0
Stenotomus chrysops	0.2	1.0	0.2
Cynoscion regalis	0.2	0.0	0.4
Scomber scombrus	0.1	0.0	0.0
Anguilla rostrata	0.1	0.0	0.3
Paralichthys oblongus	0.1	0.0	0.0
Menidia spp.	0.1	0.1	10.4
Clupea harengus	0.1	0.0	0.1
Clupeidae	0.1	0.0	0.0
Urophycis spp.	0.1	0.4	0.3
Sphoeroides maculatus	0.0	0.0	0.4
Gadus morhua	0.0	0.0	0.1
Paralichthys dentatus	0.0	0.0	0.5
Merluccius bilinearis	0.0	0.0	3.0
Etropus microstomus	0.0	0.0	0.1
Microgadus tomcod	0.0	0.0	6.5
Trinectes maculatus	0.0	0.0	0.1
Gasterosteus aculeatus	0.0	0.0	9.6
Alosa spp.	0.0	0.8	0.0
Osmerus mordax	0.0	0.0	0.8
Hemitripterus americanus	0.0	0.0	0.2
Pollachius virens	0.0	0.0	0.3
Fundulus spp.	0.0	0.0	0.3
Gasterosteus wheatlandi	0.0	0.0	3.9
Cyclopterus lumpus	0.0	0.0	1.1
Alosa aestivalis	0.0	0.0	1.0
Alosa pseudoharengus	0.0	0.1	0.4
Caranx hippos	0.0	0.0	0.1
Labridae	0.0	0.3	0.0
Melanogrammus aeglefinus	0.0	0.0	0.1
Morone americana	0.0	0.0	1.3
Morone saxatilis	0.0	0.0	0.1
Opsanus tau	0.0	0.0	0.3
Pomatomus saltatrix	0.0	0.0	0.3
Raja spp.	0.0	0.0	0.9

[a] Large impingement event in July 1984 excluded.

1987a). Beginning in 1984, the number of fish impinged continued to decline as cooling-water flow remained high. Certainly, the removal of the cofferdam contributed to the reduction of impingement at Unit 2, but impingement levels were expected to remain constant instead of continuing to decline. Change in water circulation patterns caused by the start-up of Unit 3 may have contributed to the continued decline in impingement at Unit 2.

TABLE 5. The seasonal[a] δ-mean density (no. per 500 m^3) of abundant fish egg taxa collected at EN by report period (June-May).

Taxon	79-80	80-81	81-82	82-83	83-84	84-85	85-86	86-87
Tautogolabrus adspersus	6001	8298	5132	5519	7114	5745	7560	2941
Tautoga onitis	1378	2891	2628	2268	2107	2165	3264	2731
Anchoa spp.	1445	1242	1090	786	2275	5009	148	930

[a]Data seasonally restricted to May 23-July 22 for *Tautogolabrus adspersus*, to May 24-August 19 for *Tautoga onitis*, and to June 16-August 4 for *Anchoa* spp. .

TABLE 6. The seasonal[a] δ-mean density (no. per 500 m^3) of abundant fish larval taxa collected at EN by report period (June-May).

Taxon	75-76	76-77	77-78	78-79	79-80	80-81	81-82	82-83	83-84	84-85	85-86	86-87
Anchoa spp.	-	1156	932	482	2235	2542	5701	845	1434	306	1114	1270
Pseudopleuronectes americanus	170	104	137	114	287	129	237	301	212	166	83	108
Ammodytes americanus	22	96	238	119	110	137	22	28	17	10	2	12
Myoxocephalus aenaeus	16	41	21	36	38	107	72	68	50	68	34	30

[a]Data seasonal restricted to July-September for *Anchoa* spp. , to March-June for *Pseudopleuronectes americanus*, to December-April for *Ammodytes americanus*, and to February-May for *Myoxocephalus aenaeus*.

Although impingement has decreased at Unit 2, potential impacts could still occur there which would go undetected because of the elimination of routine monitoring. Therefore, a procedure was established so that operations personnel will examine and record all large impingement events (over 300 fish in a 24-hour period). Mitigative measures to reduce impingement impacts from MNPS have been incorporated and include the addition of a fish-return sluiceway at Unit 1 and continued modification of the fish-return system at Unit 3 to increase its efficiency.

Ichthyoplankton

Ichthyoplankton studies at MNPS have provided entrainment estimates, seasonal density indices, and species composition. Over 50 taxa of ichthyoplankton have been collected (Appendix I). The additional mortality due to entrainment could affect local fish populations since natural ichthyoplankton mortality rates are one of the most important controlling factors of adult fish stock abundance (Cushing and Harris 1973; Bannister et al. 1974; Cushing 1974; May 1974; DeAngelis et al. 1977).

δ-mean densities were calculated for the most abundant fish egg and larval taxa entrained (Tables 5 and 6). Cunner eggs and anchovy larvae have consistently been the most abundant taxa collected. For all dominant larvae collected at EN, there appeared to be a general pattern of high abundance in the late 1970s or early 1980s followed by a decline to present levels that were similar to the mid 1970s. Cunner, tautog, and anchovies have accounted for over 93% of eggs collected at EN; and anchovies, winter flounder, sand lance, and grubby have accounted for over 85% of the larvae collected at EN (Table 4). These taxa were selected as potentially impacted and discussed in greater detail following this section, except for winter flounder (see Winter Flounder Studies section).

The dominant ichthyoplankton taxa collected at EN were compared to taxa collected in the trawl and seine programs. Except for winter flounder, few adults of abundant ichthyoplankton taxa were collected by trawls or seines. Adult anchovies, cunner, and tautog apparently were not very susceptible to our demersal trawl or shore-zone seine sampling. Adult abundance, or stock reproductive capacity, for these three taxa was probably best measured by seasonal egg abundance. The early life history stages of scup, windowpane, skates, and silversides were rare in ichthyoplankton

collections. This indicated that their spawning and early life history strategies reduced their susceptibility of being entrained.

American sand lance

The American sand lance is found from the Arctic to Cape Hatteras (Bigelow and Schroder 1953). They are primarily pelagic plankton feeders (Richards 1982). Individuals form large schools and are found over sandy bottoms from near shore to the edge of the continental shelf (Richards 1963; Leim and Scott 1966). Sand lance mature in 1 to 2 years and spawn between December and March (Westin et al. 1979). The life span of the sand lance has been reported as 5 to 9 years (Westin et al. 1979; Grosslein and Azarovitz 1982).

The sand lance was collected in all fish ecology programs, but primarily during its larval stage in the winter and spring. It has generally contributed less than 1% to annual total impingement (Table 4), except for the previously discussed one large impingement occurrence in 1984. Few were collected in the trawl and seine samples, possibly because juveniles and adults burrow into the sand (Leim and Scott 1966), thus avoiding these gears. Eggs were rarely collected because they are demersal and adhesive (Frizsche 1978). The sand lance was the third most abundant larval species at EN and NB. Annual entrainment estimates, based on median densities, ranged from 2.8 to 66.7 million (Table 7).

TABLE 7. Annual entrainment estimates and 95% confidence intervals for American sand lance larvae entrained at MNPS.

Year	Entrainment estimate ($\times 10^6$)	95% CI
1976	18.6	14.7-23.5
1977	66.7	56.6-77.5
1978	36.4	21.9-48.6
1979	62.4	52.4-75.6
1980	66.6	57.6-83.8
1981	57.4	50.0-67.4
1982	12.4	10.4-15.6
1983	19.6	14.0-27.1
1984	13.1	10.4-15.7
1985	5.8	5.5-8.60
1986	2.8	0.0-5.00
1987	19.8	13.1-24.8

Annual larval abundance and temporal occurrences were compared based on parameters from the Gompertz function. The function fitted the data well; all R^2 values exceeded 0.94. Generally, larvae were collected from December through May, but the estimated dates of peak abundance (as determined by the inflection point) were quite variable both from year to year and between EN and NB within a year (Table 8). The α parameter was used as an index of annual abundance and it declined considerably since the early 1980s (Fig. 3). Based on the 95% confidence intervals, abundances at EN since 1982 have been significantly lower than the 1978 to 1981 period, but were similar to abundance in 1976.

TABLE 8. Estimated date of peak abundance for American sand lance based on the inflection point of the Gompertz function for stations EN and NB.

Year	EN	NB
1976	Mar 22	-
1977	Feb 3	-
1978	Jan 31	-
1979	Apr 7	Mar 5
1980	Mar 23	Mar 12
1981	Mar 21	Mar 9
1982	Apr 2	Feb 21
1983	Apr 4	Mar 7
1984	Feb 29	Jan 16
1985	Feb 15	Jan 28
1986	Mar 31	Mar 29
1987	Apr 30	Apr 15

To determine if the decline of larvae in the Millstone area was localized, data on sand lance were examined from other areas (Table 9). Their abundance in the NMFS spring trawl survey data showed a similar decrease to levels reported in the mid 1970s. Larval densities reported for the waters off the SNPS were variable and declined from the early 1980s but not as evident as seen in the vicinity of MNPS. Similar to the MNPS program, few sand lance were taken in SNPS trawls, but there was an apparent decline in the annual CPUE. From these comparisons, it was apparent that decreasing sand lance abundance occurred regionally. Apparently, adult sand lance abundance has greatly fluctuated along the Northeast Atlantic coast during the last 20 years. Meyer

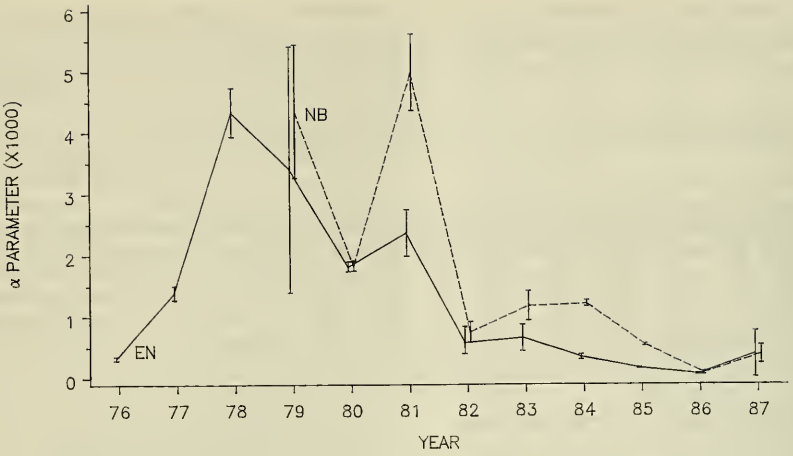

Fig. 3. American sand lance larval abundance estimates and 95% confidence intervals based on the α parameter from the Gompertz function for stations EN and NB.

TABLE 9. Annual abundance indices of American sand lance, expressed as an annual sum of means, and trawl catch as annual CPUE at Shoreham Nuclear Power Station (SNPS), and δ-mean catch of the National Marine Fisheries Service (NMFS) spring trawl survey at selected stations.

Year	Sum[a] larvae	SNSP trawls	NMFS trawls
1975	-	-	0.1
1976	-	-	123.0
1977	18463	0.11	3.8
1978	9446	1.03	249.2
1979	51545	0.61	20.0
1980	18925	0.06	145.9
1981	25989	0.66	45.9
1982	6278	0.71	37.1
1983	10165	0.68	26.3
1984	21753	0.16	7.7
1985	3284	0.00	6.5
1986	10474	0.16	0.9
1987	-	-	7.9

[a]Sums for 1977-82 based on mean density per sampling trip (Geomet Tech. 1983) and for 1983-86 based on monthly mean density (EA Eng., Sci., and Tech. 1987).

et al. (1979) reported that the average trawl catch in the spring for an area north of Cape Cod during the 1967-75 period was near 0, increased to 50 in 1976, and exceeded 10,000 in 1977. It appears that the decline of larvae in the Millstone area resulted from the regional decrease of adult stocks, which are returning to levels similar of the early to mid 1970s.

Anchovies

Two anchovy species, the bay anchovy and the striped anchovy, have been collected in the Millstone area. Based on the proportion of eggs collected for each species, the bay anchovy was by far the most common in the area (more than 95%). In addition, nearly all specimens collected by trawl and in impingement collections were the bay anchovy. Due to the preponderance of the bay anchovy and the difficulty in separating the two species in larval and juvenile stages, the remaining discussion will focus on the bay anchovy, with the relatively few striped anchovy eggs included in egg abundance estimates.

The bay anchovy is perhaps the most abundant fish along the Atlantic Coast and is usually the dominant ichthyoplankton species in estuaries within its range (McHugh 1977; Leak and Houde 1987). Its range extends from Cape Cod to Mexico, with occurrences as far north as Maine (Hildebrand 1943; Bigelow and Schroeder 1953). They are commonly found inshore during the warmer months and move offshore in the winter, but are seldom found in water deeper than 25 m (Grosslein and Azarovitz 1982). Hildebrand (1943) believed that each section of the coast had discrete anchovy populations and movements were inshore and offshore. In LIS, spawning takes place at depths of less than 20 m during June through September (Richards 1959). Eggs are pelagic and at 27°C hatch in about 24 hours (Kuntz 1914). Since water temperatures in LIS near Millstone rarely exceed 22°C, incubation probably takes longer here. Development is rapid and individuals may mature within 2.5 months of hatching in Delaware Bay, and maximum life span is probably not more than 2 or 3 years (Stevenson 1958).

Various anchovy life history stages were very abundant in some programs, but rarely collected in others. Their period of occurrence in each program has been consistent among years (NUSCO 1987b). Adults were primarily found in impingement collections from May through June, which corresponded to the spring inshore spawning migration. The estimated numbers impinged at Unit 2 have declined dramatically since 1984, particularly in 1986 and 1987 (Table 2). This was probably related to the previously discussed overall decline in Unit 2 impingement for all species. Adult anchovies were rare in the demersal trawl program. Vouglitois et al. (1987) reported large numbers of adults collected in Barnegat Bay, NJ, but their data were from semiballoon otter trawl collections as opposed to our flat otter trawl, which may have accounted for this difference. Juvenile anchovies, resulting from the summer spawning were susceptible to our trawling and were captured during August through October, primarily at NB (Appendix III). Even though anchovies ranked third in trawl catch, they were collected infrequently and in large numbers with over 70% of them collected in only 13 of the over 5,000 tows. This infrequent collection of individuals greatly limited the usefulness of trawl data as an index of abundance.

At EN, anchovy larvae ranked first among all species and was the third most abundant egg taxon (Table 4). Since over 50% of the eggs collected annually occurred during a 2- to 3-week period, spawning was during a short period of time. The annual date of peak abundance, estimated from the Gompertz function inflection point, ranged from late June to mid-July (Table 10). The date of the larval peaks did not appear to be related to the date of peak abundance for eggs, but the dates for larvae at EN and NB were similar. This similarity suggested that the factors affecting the timing of maximum abundance were probably the same throughout the Millstone area. The causes of the later larval peaks in 1978 and 1986 were not known. Any potential impact of the operation of MNPS on the anchovy population would probably be due to entrainment with annual estimates ranging from 16.0 to 807.7 million for eggs and from 1.5 to 1,284 million for larvae (Table 11). The estimated number of eggs entrained increased in 1986 relative to the previous year, because egg densities were low in 1985 and the increased cooling water demands of Unit 3 in 1986. However, this increase was not apparent

TABLE 10. Estimated date of peak of abundance anchovy larvae at EN and NB and eggs at EN based on the inflection point of the Gompertz function.

	Eggs at	Larvae at	
Year	EN	EN	NB
1976	-	Jul 22	-
1977	-	Jul 23	-
1978	-	Aug 16	-
1979	Jul 13	Jul 21	Jul 18
1980	Jul 18	Jul 20	Jul 19
1981	Jul 12	Jul 21	Jul 21
1982	Jul 7	Jul 15	Jul 11
1983	Jul 28	Jul 18	Jul 12
1984	Jun 28	Jul 18	Jul 12
1985	Jul 16	Jul 17	Jul 18
1986	Jul 4	Aug 13	Aug 9

TABLE 11. Annual entrainment estimates and 95% confidence intervals for anchovy eggs and larvae at MNPS.

Year	Eggs		Larvae	
	Entrainment estimate ($X10^6$)	95% CI	Entrainment estimate ($X10^6$)	95% CI
1976	-	-	448.4	334.2- 576.4
1977	-	-	162.5	119.0- 248.4
1978	-	-	160.0	111.6- 236.9
1979	464.1	366.0- 540.0	600.9	432.6- 766.5
1980	183.1	47.2- 250.4	558.1	480.9- 707.1
1981	369.3	285.2- 462.1	1284.1	1061.5-1531.9
1982	213.6	148.1- 277.0	299.7	229.6- 396.3
1983	503.5	348.2- 700.2	485.6	346.3- 678.2
1984[a]	807.7	388.3-1249.9	91.3	59.3- 159.4
1985	16.0	0.0- 53.70	454.9	375.6- 750.3
1986	347.9	142.7- 533.0	238.5	71.5- 398.7

[a]Revised larval estimates due to error in previous calculations (NUSCO 1987b).

for larval entrainment because Unit 3 was shutdown from July 25 to August 17, 1986 during the period of peak larval abundance; the total entrainment estimate was a function of both abundance and volume of cooling water.

Examination of anchovy egg and larval annual abundances, using the α parameter from the Gompertz function as an index, showed large fluctuations for both developmental stages (Fig. 4). The Gompertz function fitted the cumulative data well (all R^2 values exceeded 0.94). During three-unit operations, egg abundance was low

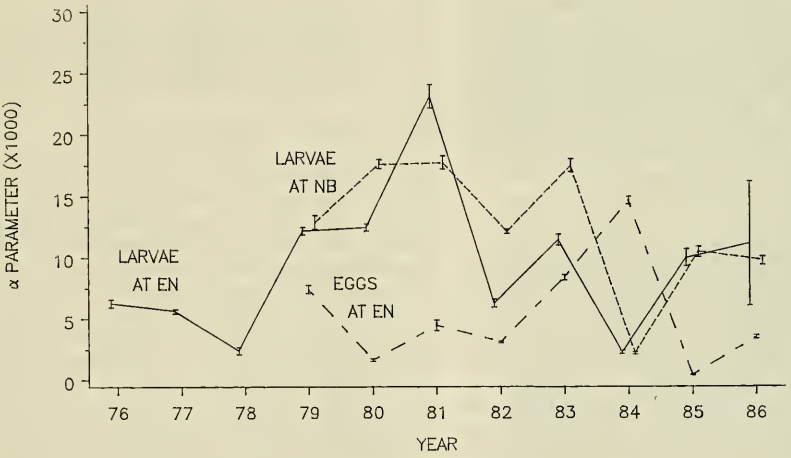

Fig. 4. Anchovy egg and larval abundance estimates and 95% confidence intervals based on the α parameter from the Gompertz function for stations EN and NB.

compared to 1983 and 1984, but similar to the period of 1980-82. Larval abundance at EN during 1986 was similar to or higher than most other years, except for 1981. The fluctuations in larval abundance at NB were similar to EN; the 1984 abundance was low at both stations. No long term-trends in abundance were apparent for eggs or larvae.

Patterns of annual abundance of anchovy eggs and larvae in the vicinity of SNPS were not similar to the Millstone area (Table 12). The low abundances of eggs at Millstone in 1985 and 1986 were not found at SNPS, which had high annual egg abundance during this period. Further, the peak that occurred in 1984 at Millstone was not evident at SNPS. During the early 1980s, larval abundance at Millstone was the highest, but at SNPS it was the lowest. These dissimilarities suggest that the spatial distribution of anchovies in LIS may differ from year to year. Trawl catches of anchovies at SNPS were variable, but a decline has occurred since the early 1980s, and similar to our trawl data, a majority of the catch was taken in late summer and early fall, probably of young-of-the-year.

TABLE 12. Annual abundance indices of anchovy eggs and larvae, both expressed as an annual sum of means; and trawl catch as annual CPUE at Shoreham Nuclear Power Station.

Year	Sum[a] eggs	Sum[a] larvae	Trawl CPUE
1977	126369	38849	1.02
1978	36687	4475	0.09
1979	100589	6129	0.74
1980	32388	934	10.82
1981	3587	1245	1.08
1982	6756	839	3.75
1983	173171	16638	0.17
1984	49565	6261	0.02
1985	109688	15440	0.00
1986	107613	9728	0.56

[a]Sums for 1977-82 based on mean density per sampling trip (Geomet Tech. 1983) and for 1983-86 based on monthly mean density (EA Eng., Sci., and Tech. 1987).

A comparison of the annual abundance of eggs and larvae at EN indicated two apparent discrepancies. First, the index of annual abundance (α) for eggs was generally lower than for larvae, and secondly, there was no relationship between the annual egg and larval abundances. The apparent low abundance of eggs relative to larvae may be related to the length of time that each developmental stage was available for capture; the incubation period for eggs was only a few days and larvae were available for capture over a period of weeks. In order to make a direct comparison of abundance of eggs to larvae, the abundance index would have to be weighted according to the average developmental time for each respective stage. Another possible explantion for low egg abundance, compared to larval abundance, was that Niantic Bay was not a primary spawning area for anchovies and that larvae were transported by tidal currents to the bay from more preferred spawning grounds.

In either of the above two cases, there should be some relationship between the abundance of eggs (a measure of spawning stock size) and the resulting larvae, unless there were annual fluctuations in the mortality rates of eggs and larvae. In some years there appeared to be an inverse relationship between egg and larval abundances. Vouglitois et al. (1987) reported a similar pattern for the bay anchovy in Barnegat Bay, NJ during a 2-year period. This would suggest that compensatory mortality occurred during the early life history stages. Density-dependent mortality was examined by comparing annual α values for eggs (E) to the δ-mean density of larvae (L) collected during August at EN. Compensatory mortality was evident, as the slope (β) was negative and significantly different from zero (Fig. 5). This relationship was most evident in 1981 which had relatively low egg abundance and the greatest larval abundance, and in 1984, with the greatest egg and the lowest larval abundance. Compensatory mortality can be caused by several factors, including starvation due to competition for prey and increased predatory pressure. Houde (1977, 1978a, 1978b) found in laboratory studies that food prey availability affected the survival of the

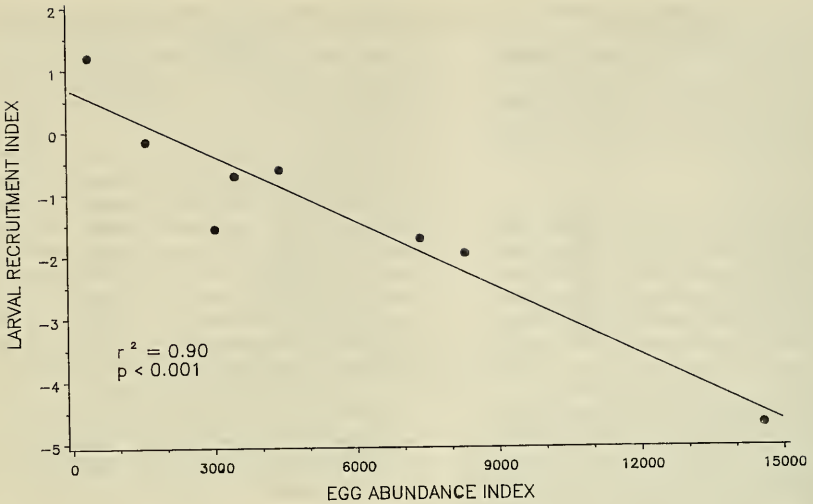

Fig. 5. Linear relationship between the larval anchovy recruitment index and the egg abundance index, suggesting density-dependent mortality in the early life history stages.

bay anchovy larvae. However, Leak and Houde (1987) reported that in a field study the highest anchovy mortality was during egg and yolk-sac stages and estimated that mortality due to predation was two to three times higher than that attributed to starvation. Cannibalism by adults may be a source of predation and because adult abundance is directly related to egg abundance, this would be a self-regulating mechanism. Causal mechanisms for the compensatory mortality of the early life history stages of anchovies in the Millstone area are not known, but because compensation was occurring at the same time as entrainment through MNPS, this would help mitigate the impact on the adult anchovy population.

Sticklebacks

The threespine stickleback and the blackspotted stickleback are small, nearshore fishes. The threespine stickleback is distributed throughout the north polar regions and as far south as Chesapeake Bay in the Western North Atlantic; the blackspotted stickleback is found only in the Western North Atlantic from Newfoundland to LIS (Perlmutter 1963).

Threespine and blackspotted sticklebacks are very similar in appearance and are not easily distinguished (Bigelow and Schroeder 1953). Because of this similarity, the blackspotted stickleback was not identified in MNPS collections until October 1981 (NUSCO 1982). Although Fitzgerald and Whoriskey (1985) found no size overlap between these two species in Canada, the length frequency of individuals collected at MNPS overlapped at 30 to 55 mm (Fig. 6). Thus, length frequency could not be used to separate the species in earlier years and the data for the two species were combined.

Sticklebacks were collected in all sampling programs, but were only abundant in impingement samples from fall through spring. During the

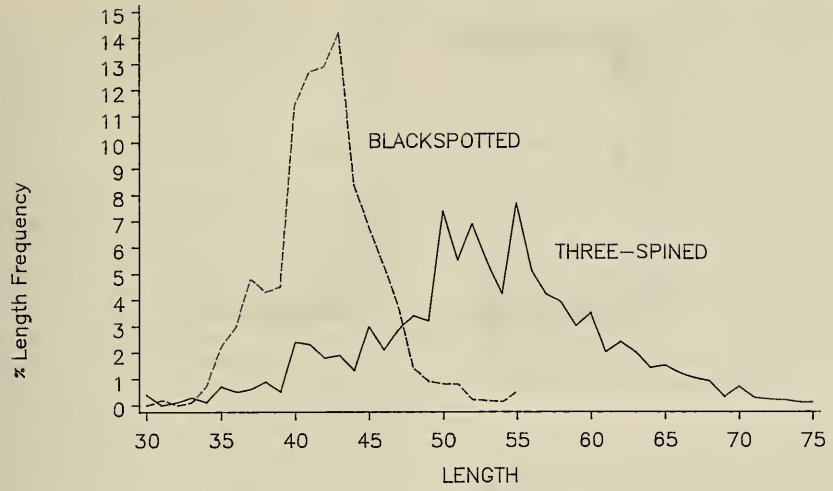

Fig. 6. Length-frequency distribution by 1-mm increments of threespine and blackspotted sticklebacks impinged at MNPS Unit 2 from 1982 through 1987.

spring, both species move into salt marshes and tidal rivers to spawn (Worgan and Fitzgerald 1981) and both adults and young-of-the-year remain in the spawning areas until late summer (Fitzgerald 1983). These spawning habits probably accounted for the low catch of these species during the summer. The number of sticklebacks impinged annually at Unit 2 ranged from 16,329 in 1983 to 880 in 1985 (Table 2). Approximately 32% of all sticklebacks impinged there were taken in 1983 and there has been a decrease in impingement since the mid-1980s to levels similar to the mid and late 1970s. The impact of impingement on these two species at MNPS has been mitigated with the addition of sluiceways at Units 1 and 3 and high survival estimates for returned fish of over 90% and 70%, respectively (NUSCO 1988).

Atlantic tomcod

The Atlantic tomcod is the most abundant member of the cod family collected in the MNPS monitoring programs. It ranges along the Atlantic coast of North America from Newfoundland to Virginia (Bigelow and Schroeder 1953).

The Atlantic tomcod was caught in all sampling programs, but was only abundant in impingement and trawl samples. Eggs are adhesive and found attached to the substrate and larvae tend to remain in brackish water spawning areas (Howe 1971), habitats not sampled by the monitoring programs. Tomcod reach sexual maturity at about 130 mm (Howe 1971) and over 98% of those impinged were adults larger than 130 mm (Fig. 7). About 90% of those impinged were taken in the fall and winter, during the time of their spawning migration (Howe 1971; Klauda et al. 1987). Over 40% of the total impingement at Unit 2 since 1976 occurred in 1982 (Table 2). A marked decrease

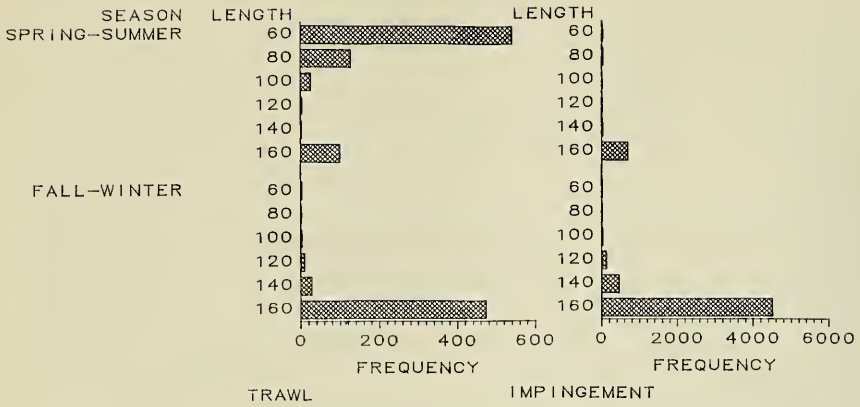

Fig. 7. Spring-summer and fall-winter seasonal length-frequency distribution by 20-mm size-classes of Atlantic tomcod in trawl and MNPS Unit 2 impingement collections from 1976 through 1987.

occurred in the number impinged since three-unit operations. In trawls, over half of the tomcod were caught at the nearshore stations (NR and JC). Young-of-the-year dominated the trawl catches in the spring and summer; adults were caught mostly in the fall and winter (Fig. 7). Trawl catches peaked from April through June, except at NR, where most were caught during their winter spawning season.

The annual abundances of tomcod in trawls were analyzed using the δ-mean as an index of relative abundance; only data from catches at NR and JC were sufficient to determine annual trends (Table 13). Annual δ-mean catches were low and during 2 report periods (1980-81 and 1985-86), none were found at JC. The Atlantic tomcod is a short-lived species and becomes sexually mature during the fall of its first year (Klauda et al. 1987). Marine fishes that are short-lived usually exhibit large year-to-year variations in abundance because population size is determined in a single spawning season and conditions during that season often control spawning success. This is evident in the distribution of annual catches at JC. In 1980-81, no tomcod were collected at this station, but 3

TABLE 13. The annual δ-mean catch (CPUE) and 95% confidence interval of Atlantic tomcod caught by trawls at stations JC and NR for each report period (June-May).

Year	JC	NR
1976-77	0.3 ± 0.3	0.1 ± 0.2
1977-78	0.5 ± 0.7	0.2 ± 0.3
1978-79	0.2 ± 0.4	0.3 ± 0.2
1979-80	0.2 ± 0.4	0.2 ± 0.2
1980-81	0	2 ± 1.8
1981-82	0.04 ± 0.08	3 ± 6.9
1982-83	0.08 ± 0.1	1 ± 0.7
1983-84	0.3 ± 0.4	0.3 ± 0.2
1984-85	0.2 ± 0.1	0.3 ± 0.2
1985-86	0	0.7 ± 0.5
1986-87	0.04 ± 0.08	0.07 ± 0.1

years later (1983-84) the δ-mean catch was one of the highest recorded. The 1986-87 catches were low at both stations but will probably rebound when conditions are better suited for reproductive success.

Silversides

Two species of silversides dominate the shore zone along the Connecticut coast, the Atlantic silverside and the inland silverside. Both species are sympatric along the Atlantic coast, with the Atlantic silverside ranging from the Gulf of St. Lawrence to the Chesapeake Bay and the inland silverside ranging from Cape Cod to South Carolina (Johnson 1975). Both species spawn as yearlings and have a life cycle that ranges from 1 to 2 years. Both are omnivorous, feeding on copepods, mysid shrimp, fish eggs, and young squid. They are important as forage food for larger fish species (Bigelow and Schroeder 1953).

Silversides collected in MNPS programs were not always identified to species. When identified, the Atlantic silverside was the most abundant (over 90%). However, to determine long-term trends the two species were analyzed as a single taxon. Silversides dominated seine collections, accounting for over 80% of the total catch (Appendix IV). They were also among the top-ranked taxa collected in the trawl and impingement programs (Tables 1 and 4). Silversides were not abundant in plankton samples because their eggs are adhesive (Bigelow and Schroeder 1953) and larvae and juveniles stay close to shore (Bayliff 1950).

Seasonal patterns of abundance occurred in the seine, trawl, and impingement collections. They were found in seine collections in the spring, summer, and fall and in trawl and impingement collections during the winter. This pattern suggested that silversides in the MNPS area overwintered in waters close to shore. Offshore winter migrations of silversides have been reported in other studies (Bayliff 1950; Bigelow and Schroeder 1953; Conover 1979; Conover and Murawski 1982). Conover (1979) found that silversides in Massachusetts migrated about 50 km offshore in winter to depths of 100 m and only 1% of the population returned inshore the following spring. In the MNPS area, the rate of return (mean number per haul in the fall compared to the spring) was calculated starting in 1984, the first year sampling was done at least once a month and biweekly from April through October. The average return rate at the three stations ranged from about 9% in 1985 to about 40% in 1986. Silversides in LIS may have a different overwintering strategy than fish that overwinter in the Gulf of Maine. Winter water temperatures in LIS do not approach the 1°C lethal limit for silversides (Hoff and Westman 1966), but average 2.5-4°C. Thus, silversides in LIS may not have to move as far offshore to find tolerable winter water temperatures.

Because of the additional thermal effluent in Jordan Cove, a potential exists for changes in the distribution of silversides inhabiting the shorezone at JC and WP. Sampling at these two sites and at control station GN was doubled in 1984 from monthly to biweekly (April through October) to increase our ability to detect any changes. Annual δ-mean catches were calculated for each of the three seine sites (Table 14). The 1986

TABLE 14. Seasonal[a] δ-mean catch (CPUE) and 95% confidence interval of silversides by seine.

Year	JC	GN	WP
1976[b]	–	–	–
1977	1251 ± 2094	151 ± 569	62 ± 168
1978	26 ± 20	32 ± 64	24 ± 35
1979	41 ± 55	26 ± 27	15 ± 12
1980	479 ± 930	104 ± 96	55 ± 70
1981	114 ± 107	81 ± 72	31 ± 40
1982	108 ± 102	48 ± 112	192 ± 567
1983	580 ± 989	42 ± 59	112 ± 158
1984	35 ± 35	11 ± 9	3 ± 1
1985	23 ± 14	18 ± 11	6 ± 4
1986	200 ± 404	58 ± 48	16 ± 10

[a] Season used for calculating δ-mean was June-November at all stations

[b] Not enough data available in 1976 to calculate δ-mean

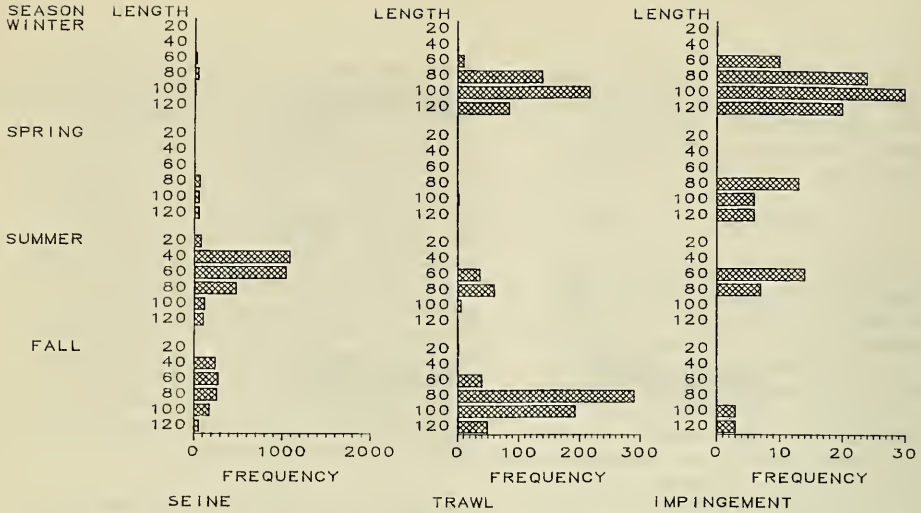

Fig. 8. Seasonal length-frequency distribution by 20-mm size-classes of silversides in seine, trawl, and MNPS Unit 2 impingement collections during 1986 and 1987.

catches were within the range of historic data. The length-frequency distribution of the 1986 catch was compared to the long-term frequency, and the size composition found in 1986 was similar to previous data (NUSCO 1987b; Fig. 8). Seasonal patterns of occurrence in 1986-87 were also similar to historic patterns.

The estimated 136 silversides impinged in 1987 was a historic low. The pattern of decreased impingement was previously discussed and was not specific to silversides, but was probably due to physical changes near the MNPS intakes. The δ-mean catch in trawls, an index of winter adult abundance, for the 1986-87 report period was similar to previous catches (Table 15), indicating that the decrease in impingement was not due to a change in adult abundance.

TABLE 15. Seasonal[a] δ-mean catch (CPUE) and 95% confidence interval of silversides by trawls at selected stations by report period (June-May).

Report period	IN	JC	NB	NR
1976-77	15 ± 16	13 ± 20	6 ± 8	77 ± 283
1977-78	29 ± 92	6 ± 612	18 ± 25	10 ± 21
1978-79	60 ± 105	9 ± 8	8 ± 7	2 ± 1
1979-80	42 ± 276	6 ± 16.8	0.7 ± 1.6	4 ± 6
1980-81	8 ± 17.4	4 ± 4.6	19 ± 41.5	3 ± 3.8
1981-82	6 ± 9.2	0.7 ± 0.4	5 ± 6.4	6 ± 8
1982-83	2 ± 3.5	1 ± 2.4	0.5 ± 12.5	12 ± 4.7
1983-84	2 ± 4.2	4 ± 1.3	4 ± 0.6	1 ± 6.3
1984-85	2 ± 6.3	5 ± 11.3	1 ± 1.4	0.5 ± 0.9
1985-86	7 ± 8.2	6 ± 7.6	2 ± 1.4	3 ± 5.9
1986-87	5 ± 3.1	8 ± 6.9	4 ± 2.9	110 ± 222

[a]Season used for calculating δ-mean was November-February at IN, NB and NR and October-January at JC.

Grubby

The grubby is found in coastal waters, commonly in eelgrass habitats, along the Atlantic coast of North America from the Gulf of St. Lawrence to New Jersey (Bigelow and Schroeder 1953). They spawn throughout the winter (Lund and Marcy 1975) and Richards (1959) reported finding larvae in shallower areas of LIS from February to April. The grubby tolerates a wide range of temperatures and salinities (Bigelow and Schroeder 1953).

The grubby is a resident in the Millstone area and both larvae and adults were collected in the monitoring programs. However, eggs were rarely taken because they are demersal and adhesive (Lund and Marcy 1975). Juveniles and adults were rarely collected in the shore zone by seine.

Grubby larvae accounted for about 4% of the total larval collection in entrainment samples (Table 4). Annual entrainment estimates have ranged from 8.9 to 50.0 million and the estimates during three-unit operations were similar to those in previous years during the 1980s, even with the addition of Unit 3 (Table 16). Larvae were collected at both EN and NB, primarily in February through May and the dates of peak abundance varied from mid March to early April (Table 17). The α parameters calculated from the Gompertz equation (all R^2 values exceeded 0.98) were used as indices of annual larval abundance (Fig. 9). Larvae were most abundant from 1981 to 1983 at EN and the abundance during 1984 to 1987 decreased to a level similar to the late 1970s. Annual abundance at NB was consistently lower than at EN. Larval abundances during three-unit operation were within the range of historical data at EN and NB.

TABLE 16. Annual entrainment estimates and 95% confidence intervals for grubby larvae at MNPS.

Year	Entrainment estimate ($x10^6$)	95% CI
1976	12.0	10.1-15.2
1977	30.2	24.9-33.7
1978	8.9	7.3-10.8
1979	19.8	17.9-22.2
1980	30.2	25.8-37.1
1981	45.0	33.4-51.7
1982	46.4	41.8-57.2
1983	50.0	41.6-63.5
1984	35.8	29.0-42.7
1985	36.5	28.9-42.5
1986	47.1	38.0-61.0
1987	45.5	32.0-58.4

TABLE 17. Estimated date of peak abundance for grubby larvae based on the inflection point of the Gompertz function for stations EN and NB.

Year	EN	NB
1976	Mar 23	-
1977	Apr 7	-
1978	Mar 20	-
1979	Mar 27	Mar 21
1980	Mar 23	Mar 22
1981	Apr 4	Apr 4
1982	Mar 28	Apr 1
1983	Mar 14	Mar 27
1984	Mar 11	Mar 12
1985	Mar 24	Apr 5
1986	Mar 17	Mar 22
1987	Mar 15	Mar 14

In impingement collections, the grubby was the third most abundant taxon, accounting for over 11% of the total (Table 4). Most were adults (60 to 120 mm) taken during their winter spawning season (December through April). As was found for other species, there was a recent decline in impingement at Unit 2 with the estimated number in 1987 the lowest recorded (Table 2).

Almost 80% of the grubby taken by trawl were found at the nearshore stations (IN, JC, and NR) (Appendix III). They were collected throughout the year at JC and NR, and primarily during their spawning season at IN. At these stations, δ-mean catches during three-unit operations were within the historical range (Table 18). Highest annual catches at IN and NR occurred in the early 1980s and corresponded to high larval abundance at EN during the same time period. The annual mean length at IN and JC has remained fairly consistent, but at NR mean length decreased during the 1980s (Fig. 10). This smaller mean length at NR

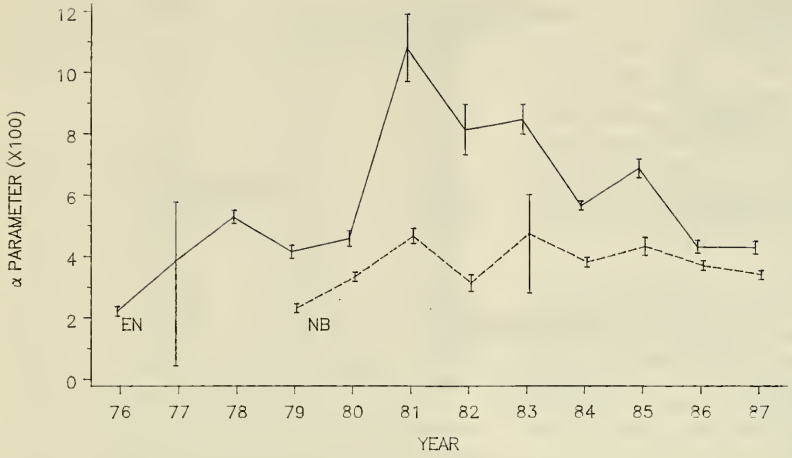

Fig. 9. Grubby larval abundance estimates and 95% confidence intervals based on the α parameter from the Gompertz function for stations EN and NB.

was concurrent with larger catches and suggested higher recruitment of young.

TABLE 18. Seasonal[a] δ-mean catch (CPUE) and 95% confidence intervals of grubby caught by trawl at selected stations during each report period (June-May).

Report period	IN	JC	NR
1976-77	1 ± 0.4	1 ± 1.1	1 ± 0.8
1977-78	2 ± 0.9	2 ± 1.1	0.5 ± 0.4
1978-79	1 ± 0.5	2 ± 1.3	1 ± 0.5
1979-80	2 ± 0.9	1 ± 0.3	5 ± 3.0
1980-81	2 ± 1.3	1 ± 0.4	2 ± 1.7
1981-82	5 ± 2.7	0.7 ± 0.4	9 ± 8.2
1982-83	5 ± 3.1	0.7 ± 0.3	16 ± 9.5
1983-84	2 ± 0.6	2 ± 0.6	5 ± 2.8
1984-85	2 ± 3.3	0.8 ± 0.6	7 ± 4.1
1985-86	2 ± 0.7	0.6 ± 0.3	4 ± 2
1986-87	0.9 ± 0.3	0.7 ± 0.5	8 ± 6.4

[a]Season used for calculating the δ-mean was December-June at IN and year-round at JC and NR (June-May).

Except at NR, no long-term changes in mean length or abundance indices occurred for the grubby, even though it was a dominant taxon in both entrainment and impingement. The estimated number impinged has declined since 1985, but there has been no decline in trawl catch, indicating this was probably a result of physical changes (removal of the cofferdam) near the Unit 2 intake. Impingement impacts for the grubby have been reduced with the addition of sluiceways at MNPS. The grubby is a hardy species and had high sluiceway survival of 74% at Unit 1 and 97% at Unit 3 (NUSCO 1988).

Tautog

The tautog is found from New Brunswick to South Carolina, but is most common from Cape Cod to the Delaware Capes (Cooper 1965). Its distribution is limited primarily to inshore regions with individual populations being highly localized (Cooper 1966). They are commonly found in

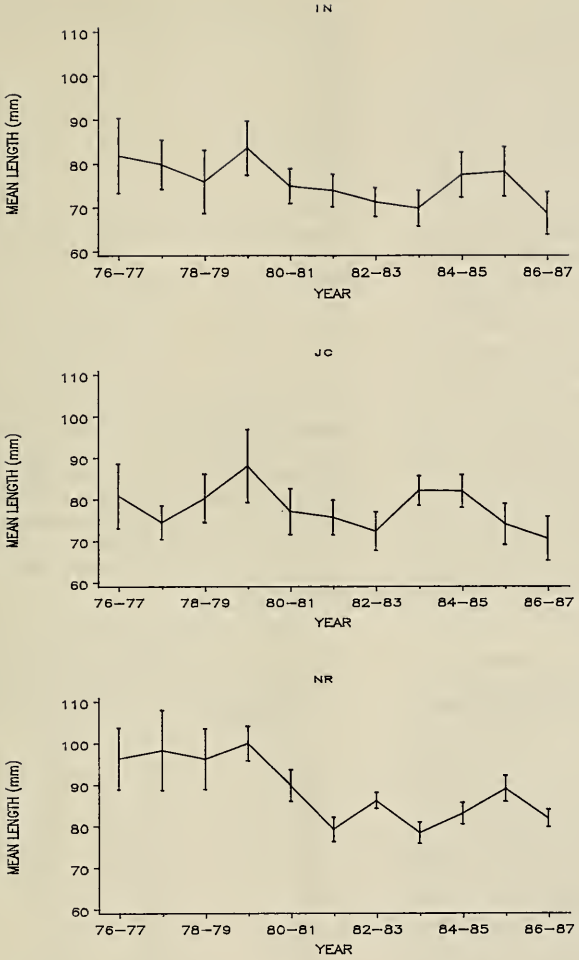

Fig. 10. The annual mean length and 95% confidence interval of grubby taken by trawl at stations IN, NR, and JC.

waters less than 20 m around rocky areas, ledges, mussel beds, breakwaters, and other similar nearshore habitats from early May until late October (Bigelow and Schroeder 1953; Wheatland 1956; Cooper 1965). Juveniles are also found in eelgrass beds and among macroalgae in coves and channels (Tracy 1910; Briggs and O'Conner 1971). Both juveniles and adults have a home site where they remain inactive and under cover at night; during the day larger fish move to other locations to feed, but juveniles remain close to their home sites (Olla et al. 1974). During winter, adults move to deeper water (about 25 to 55 m) and remain inactive while juveniles stay inshore to overwinter in a torpid state (Cooper 1965; Olla et al. 1974). Tautog males become sexually mature at age 2-3 and females at age 3-4 and the maximum reported age for males is 34 years and females is 22 years (Chenoweth 1963; Cooper 1965). Spawning occurs from mid-May until mid-August in LIS (Wheatland 1956; Chenoweth 1963). The eggs are pelagic, hatch in 42-45 hours at 22°C, and are concentrated in the upper 5 m of the water column (Williams 1967; Fritzsche 1978). Young become benthic and move inshore after metamorphosis, which is completed by 10 mm (Fritzsche 1978).

The tautog was collected in all sampling programs, but only in high abundance as eggs from May through August. Due to its habitat preference, it was rarely collected in the shore-zone seine program (Appendix IV). Even though tautog prefer rocky shores, such as those adjacent to the MNPS intakes, they were not impinged in large numbers and contributed less than 2% to the total impingement estimate; annual estimates at Unit 2 ranged from 96 in 1986 to 731 in 1978 (Table 2). Annual δ-mean abundance indices could not be calculated from trawl data because individuals were collected infrequently. Because trawl sampling effort was nearly the same each year, the total catch from each station and report period (June-May) was used to examine spatial and temporal distributions (Table 19). Tautog were caught primarily at nearshore stations (JC, IN, and NR). The lowest catches at NB have occurred in recent years, but this decline was not evident at the other stations. Some of the largest annual fluctuations have occurred at NR. Mean length has remained fairly constant at all stations, except at NR (Fig. 11). The decline in mean length at NR was concurrent with increased abundance, particularly evident in the 1981-82, 1982-83, and 1986-87 report periods, indicating greater recruitment of young. Similar to the Millstone area, no trends were apparent in trawl CPUE at SNPS (Table 20).

TABLE 19. Total number of tautog caught by trawl at each station during each report period (June-May)./

Report period	JC	NR	NB	TT	BR	IN
1976-77	71	39	20	26	10	63
1977-78	106	16	35	29	27	70
1978-79	59	30	43	15	30	86
1979-80	57	45	32	26	42	68
1980-81	22	25	27	10	15	47
1981-82	20	129	23	6	23	27
1982-83	37	90	23	26	13	50
1983-84	18	16	23	15	27	41
1984-85	15	11	18	9	20	46
1985-86	31	22	7	11	16	47
1986-87	57	110	2	4	19	23
Total	493	533	253	177	242	568

TABLE 20. Annual abundance indices of tautog eggs and larvae, both expressed as an annual sum of means, and trawl catch as annual CPUE at Shoreham Nuclear Power Station.

Year	Sum[a] eggs	Sum[a] larvae	Trawl CPUE
1977	17727	424	0.76
1978	5930	197	0.33
1979	11337	113	0.61
1980	1711	50	0.63
1981	4062	12	0.40
1982	3239	[b]	0.28
1983	3428	99	0.34
1984	4415	b	0.19
1985	6003	168	0.32
1986	11562	166	0.29

[a]Sums for 1977-82 based on mean density per sampling trip (Geomet Tech. 1983) and for 1983-86 based on monthly mean density (EA Eng., Sci., and Tech. 1987).

[b]Abundance not reported (Geomet Tech 1983) apparently due to low densities.

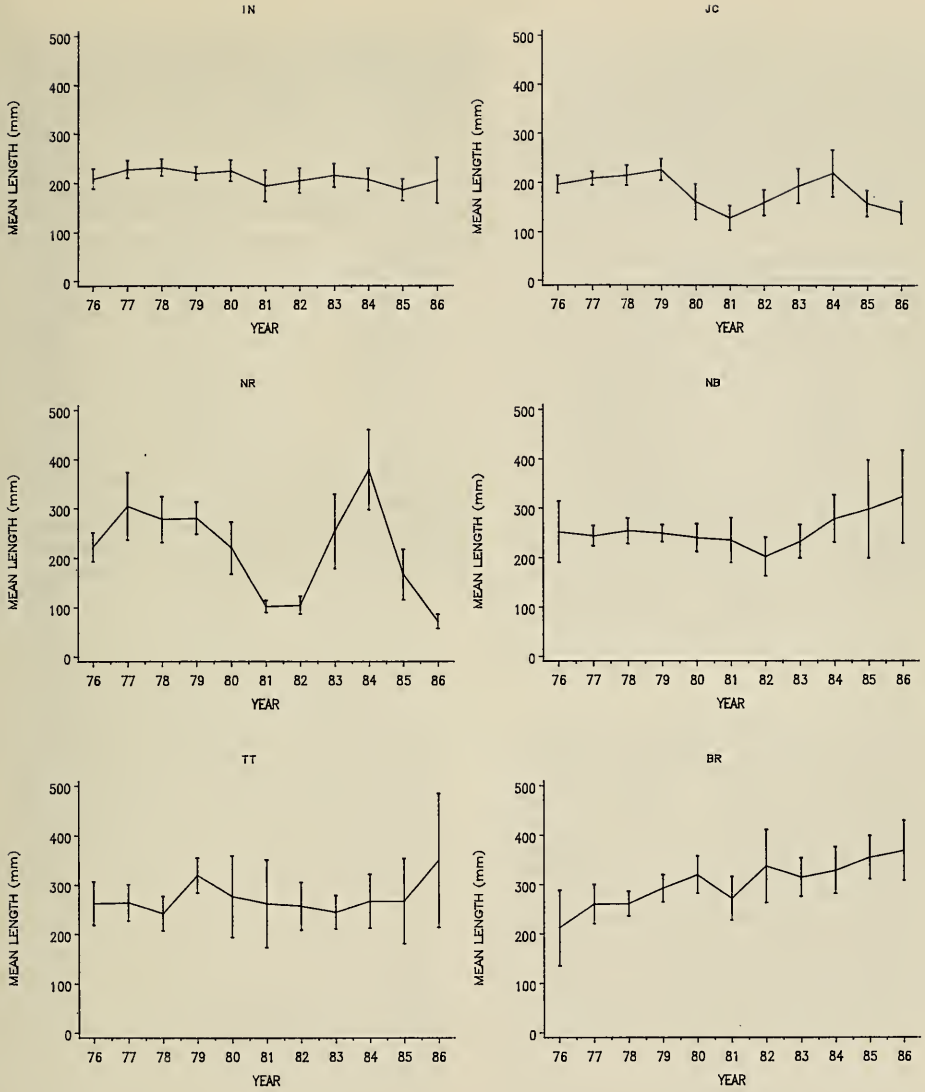

Fig. 11. The annual mean length and 95% confidence interval of tautog taken by trawl at each station.

Probably the greatest potential impact to the tautog from three-unit operations is from the entrainment of eggs. The entrainment estimate for 1986 was at least twice that of previous years (Table 21). The Gompertz function was fitted to the annual cumulative egg densities at EN (all R^2 values exceeded 0.98) and the α parameter was used to compare abundances. Annual egg abundance fluctuated from a low in 1979 to relatively high abundances in 1985 and 1986 (Fig. 12). The time of peak abundance (estimated from the inflection point of Gompertz function) generally occurred mid to late June (Table 22).

TABLE 21. Annual entrainment estimates and 95% confidence intervals for tautog eggs at MNPS.

Year	Entrainment estimate ($x10^6$)	95% CI
1979	645.8	508.5- 809.7
1980	992.1	836.5-1158.2
1981	1385.3	1201.5-1655.4
1982	1443.4	1181.1-1579.0
1983	953.7	718.7-1275.2
1984	1211.9	915.9-1543.2
1985[a]	1435.9	1037.2-2416.1
1986	3163.7	2597.5-4021.1

[a] Revised estimate due to error in previous calculations (NUSCO 1987b).

TABLE 22. Estimated date of peak abundance for tautog eggs based on the inflection point of the Gompertz function for station EN.

Year	EN
1979	Jun 23
1980	Jun 22
1981	Jun 21
1982	Jun 28
1983	Jun 21
1984	Jun 23
1985	Jun 17
1986	Jun 12

Tautog larvae did not appear consistently in ichthyoplankton samples during their period of occurrence and when present, occurred in low densities. Due to the numerous zero values for sample densities, larval entrainment estimates,

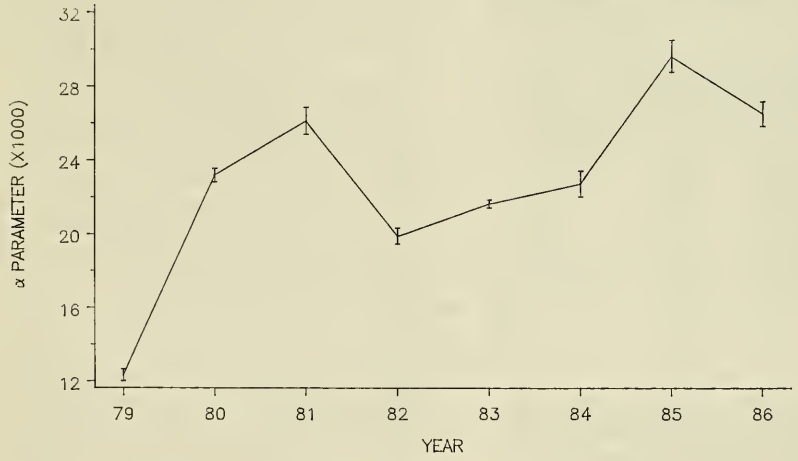

Fig. 12. Tautog egg abundance estimates and 95% confidence intervals based on the α parameter of the Gompertz function for station EN.

based on medians, could not be calculated. The seasonal δ-mean densities were used as an abundance index (Table 23). Larval densities have been consistently higher at NB than at EN, but similar annual trends were evident at both stations; abundance increased from the late 1970s to early 1980s and then declined to levels comparable to those in the mid-1970s. This decline was not evident in annual egg abundances.

TABLE 23. The seasonal[a] δ-mean density (no. per 500 m^3) of tautog larvae collected at stations EN and NB by year.

Year	EN	NB
1976	37.3 ± 16.0	—
1977	36.3 ± 15.3	—
1978	1.2 ± 0.6	—
1979	11.6 ± 4.8	50.8 ± 22.6
1980	46.9 ± 17.8	91.5 ± 50.0
1981	82.9 ± 36.0	92.5 ± 62.0
1982	44.4 ± 21.9	111.8 ± 60.0
1983	34.1 ± 21.1	124.2 ± 129.5
1984	3.1 ± 2.1	29.2 ± 21.1
1985	18.2 ± 12.7	44.2 ± 15.0
1986	3.2 ± 1.8	12.2 ± 6.7

[a] Data seasonally restricted to June through August.

Comparison of annual egg to larval abundances, based on the δ-mean (see Table 5 for egg δ-mean), indicated that egg to larval survival was low; generally the larval index was less than 2% of of the corresponding egg index. Similar low annual larval to egg ratios were evident for collections at SNPS (Table 20). Further discussion of this low survival for the wrasses (tautog and cunner) is provided in the following section on cunner. This apparent low natural egg survival would reduce the potential impact of the large numbers of eggs entrained by three-unit operations. A comparison of annual larval and egg abundances did not reveal a density-dependent relationship, as was found for anchovies. Because the tautog takes 2 to 4 years to reach maturity, the possible impact of entrainment by three-unit operation on the adult stock size (best measured by annual egg abundance) will not be evident for several years.

Cunner

The cunner is a coastal marine fish that prefers rocky habitats (Bigelow and Schroeder 1953; Serchuk 1972; Olla et al. 1975, 1979; Dew 1976; Pottle and Green 1979). It ranges from northern Newfoundland to the mouth of the Chesapeake Bay (Leim and Scott 1966). Most cunner have limited home ranges (less than 4 km) and probably stay within several meters of their nighttime shelter. Adults generally display highly localized abundance in areas they inhabit and their numbers greatly decrease only a short distance from cover (Gleason and Recksiek, in preparation). They are active only during the day and activity declines in cold weather as individuals become dormant at temperatures below 8°C and lie torpid among and under rocks (Green and Farwell 1971; Green 1975; Dew 1976; Olla et al. 1979). Individuals mature in 1 to 2 years and the maximum reported age is 10 years (Johansen 1925; Dew 1976). Cunner spawn primarily in June through August and the pelagic eggs hatch in 2-6 days depending on water temperature (Williams 1967; Dew 1976; Fritzsche 1978). Metamorphosis of larvae is complete by 10 mm and juveniles move to the bottom (Miller 1958).

All life stages of the cunner were collected in the Millstone area. Eggs and larvae were found in ichthyoplankton collections, primarily from June through August. Juveniles and adults were caught at all six trawl stations and in greatest abundance during the spring through fall. Cunner were rarely collected by seine (Appendix IV). As cunner prefer the rocky habitats that surround MNPS, the species was among the top dozen of those impinged (Table 2). Annual impingement estimates at Unit 2 decreased from a high of 1,787 in 1983 to a low of 57 in 1987. This decrease followed the general decline in total impingement of all species.

Cunner eggs predominated in entrainment collections and were abundant during May through July; the date of peak abundance consistently occurred during the first half of June (Table 24).

TABLE 24. Estimated date of peak abundance for cunner eggs based on the inflection point of the Gompertz function for station EN.

Year	EN
1979	Jun 12
1980	Jun 14
1981	Jun 8
1982	Jun 18
1983	Jun 14
1984	Jun 9
1985	Jun 7
1986	Jun 5

The α parameter from the Gompertz function was used to estimate annual egg abundance and all R^2 values exceeded 0.98. Annual egg abundances peaked during 1985 and declined to a historical low in 1986 (Fig. 13). This low abundance was reflected in the annual entrainment estimates with the 1986 estimate among the smallest, even with the additional cooling water demands of Unit 3 (Table 25). Similar to tautog, cunner larval

TABLE 25. Annual entrainment estimates and 95% confidence intervals for cunner eggs at MNPS.

Year	Entrainment estimate ($x10^6$)	95% CI
1979	1674.7	1341.6-1964.3
1980	2031.8	1654.5-2971.6
1981	1610.5	1335.3-2145.5
1982	2103.0	1693.5-2903.9
1983	2589.3	1763.3-3087.9
1984	2153.6	1563.9-2595.4
1985[a]	2216.2	1415.7-3083.5
1986	1812.0	1420.1-2603.1

[a] Revised estimate due to error in previous calculations (NUSCO 1987b).

entrainment estimates based on median densities could not be calculated because larvae were inconsistently found in samples collected during their period of occurrence. The seasonal δ-mean density of larvae in 1986 was one of the lowest at both EN and NB (Table 26). Abundances

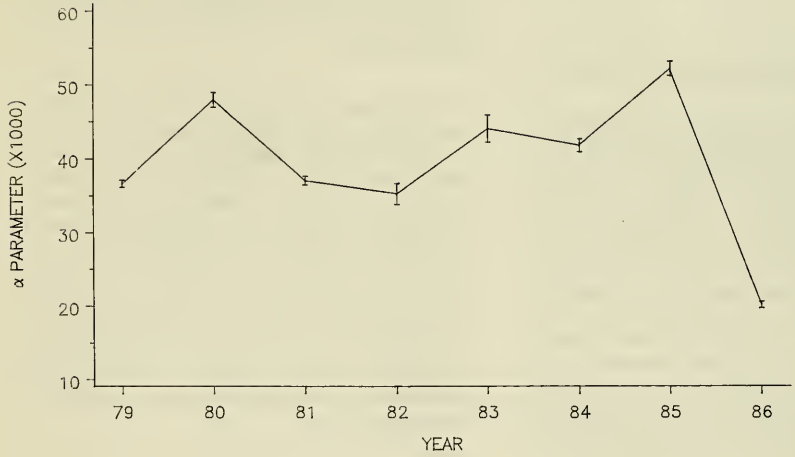

Fig. 13. Cunner egg abundance estimates and 95% confidence intervals based on the α parameter of the Gompertz function for station EN.

TABLE 26. The seasonal[a] δ-mean density (no. per 500 m^3) of cunner larvae collected at stations EN and NB by year.

Year	EN	NB
1976	29.4 ± 14.1	—
1977	58.1 ± 28.1	—
1978	1.2 ± 0.4	—
1979	13.6 ± 4.8	94.7 ± 42.2
1980	58.7 ± 19.6	148.1 ± 86.5
1981	77.4 ± 36.3	98.5 ± 72.0
1982	31.8 ± 13.7	153.0 ± 74.0
1983	49.9 ± 26.1	207.9 ± 266.0
1984	3.7 ± 2.6	37.6 ± 28.6
1985	12.6 ± 8.9	30.3 ± 11.5
1986	3.0 ± 1.6	8.4 ± 4.8

[a] Data seasonally restricted to June through August.

were found to be consistently higher at NB than EN, suggesting that larval densities may be lower near the MNPS intakes compared to other areas. Larval abundance began declining in 1984 and has not returned to historic levels. However, a similarly large decrease in larval abundance, which occurred from 1977 to 1978, was followed by an increase to relatively high densities, in the early 1980s. Low larval abundance in 1984 may have been due to predation or other factors operating concurrently on the entire summer ichthyoplankton assemblage, because larval densities of tautog and anchovies were low that year as well (NUSCO 1987b). A comparison of cunner and tautog larval abundance showed a remarkably similar pattern at both EN and NB (Tables 23 and 26). At EN, lowest densities occurred in 1978, 1984, and 1986, and the greatest densities occurred in 1981. At NB, the greatest abundances were in 1983 and lowest in 1986. However, these similarities between the two species were not evident in their egg abundance estimates.

Cunner egg survival was reported as low (about 5%) by Williams et al. (1973), based on the examination of embryonic development in field-collected eggs; this survival estimate did not take into account the possible additional loss due to predation. An index of egg survival was estimated by the ratio of the annual δ-mean for larvae to eggs (see Table 5 for egg δ-mean) at EN for cunner, and also tautog for comparison (Table 27). These low ratios indicated that few eggs survived to the larval stage. Further, survival in recent years was even less than usual and probably

TABLE 27. Ratio of annual δ-mean densities of cunner and tautog larvae to eggs collected at station EN.

Year	Cunner	Tautog
1979	0.0023	0.0084
1980	0.0071	0.0162
1981	0.0151	0.0315
1982	0.0058	0.0196
1983	0.0070	0.0162
1984	0.0006	0.0014
1985	0.0017	0.0056
1986	0.0010	0.0012

produced fewer juvenile recruits from 1984 through 1986. Egg densities seem unrelated to the corresponding larval densities and no compensatory relationship was found. Whatever factors affected survival of cunner larvae also affected tautog larvae; ranks of the larval to egg ratios were nearly the same for the two species and they were significantly correlated (Spearman rank correlation, $r = 0.83$, $p < 0.01$).

Cunner were taken only frequently enough at three (IN, JC, and NB) of the six trawl stations to use the δ-mean for describing abundances (Table 28). At all three stations there was a decline

TABLE 28. Seasonal[a] δ-mean catch (CPUE) and and 95% confidence intervals of cunner caught by trawl at selected stations.

Year	IN	JC	NB
1976	22 ± 19	4 ± 2.0	1 ± 0.7
1977	30 ± 23	3 ± 1.0	1 ± 0.6
1978	6 ± 3.7	3 ± 1.4	0.7 ± 0.3
1979	29 ± 23	9 ± 5.0	2 ± 1.0
1980	23 ± 16	6 ± 2.0	3 ± 1.2
1981	12 ± 10	5 ± 2.2	3 ± 0.9
1982	5 ± 3.0	4 ± 2.0	2 ± 0.9
1983	3 ± 1.3	4 ± 2.0	1 ± 0.6
1984	2 ± 1.0	2 ± 1.0	0.4 ± 0.2
1985	1 ± 0.6	1 ± 0.5	0.4 ± 0.7
1986	0.1 ± 0.2	0.5 ± 0.4	0.08 ± 0.1

[a] Season used for calculating δ-mean was May-August at IN, May-September at JC and April-November at NB.

in abundance, particularly at IN. Because trawl sampling effort was about the same each year, total catch was also used as an index of relative abundance for comparison among the six stations (Table 29). Decreases of juveniles and adults were

TABLE 29. Total number of cunner caught by trawl for each station during each report period (June-May).

Report period	JC	NR	NB	TT	BR	IN
1976-77	97	14	37	43	15	632
1977-78	78	4	39	34	54	666
1978-79	90	7	40	12	24	227
1979-80	232	11	55	25	54	1022
1980-81	191	7	89	42	15	596
1981-82	263	91	77	23	44	342
1982-83	209	58	77	24	36	207
1983-84	120	60	36	12	58	76
1984-85	73	16	23	20	48	68
1985-86	23	15	1	9	44	27
1986-87	28	38	16	5	51	9
Total	1404	321	490	249	443	3878

apparent at the four stations closest to MNPS (IN, NB, JC, and TT), but at BR numbers remained stable over the period and they fluctuated at NR. Most (57%) cunner were taken at IN, where numbers began to decrease in the 1980-81 report period and decreased further in 1983-84. Simultaneous decreases occurred at JC, TT, and NB, 2 years after the decline at IN began. Although causes for these declines may never be known with certainty, physical alterations of the habitat in the MNPS intake area near IN occurred just before the decreases at that station and could have accounted for the observed change. In March 1975, a bottom fish boom was installed at Unit 1 intake to reduce impingement. It was unsuccessful and was removed in the spring of 1981 just before the initial decline at IN. The Unit 3 cofferdam was constructed in March of 1976 and was removed in the summer of 1983 just before the second decline. Both of these structures provided ideal habitats for cunner. Unfortunately, trawl monitoring was not done at IN prior to the installation of these structures and it could not be determined if these structures actually caused an increase in the cunner population around the MNPS intake.

During the latest report period of 1986-87, the mean length of cunner caught by trawl decreased markedly at all stations, except at BR (Fig. 14), indicating a reduction in the abundance of older fish. To determine the age structure of the local population at the three trawl stations where they were most abundant (JC, NB, and IN), cunner were assigned to age-classes using an age-length key (Serchuk 1972). From 1976-77 through 1980-81, ages I, II, and III were dominant (Table 30). The low percentage of age 0 (young-of-the-year) during this time period indicated that the trawl may not have sampled smaller individuals as effectively as larger ones. In 1981-82, age 0 became the dominant age-class. The estimated number of age 0 fish was significantly correlated to the δ-mean density of larvae at EN during the same time period (Spearman rank correlation, $r = 0.71$, $p = 0.015$). Although sample size was small, over 80% of the cunner taken in 1986-87 at the three stations near MNPS were age 0. These findings showed that older cunner were less abundant near MNPS. This predominance of younger fish and low abundance during the 1986-87 report period probably accounted for the decease in eggs collected at EN during the same period.

TABLE 30. Percentage of cunner by estimated age-class[a] caught by trawl at JC, NB and IN combined during each report period (June-May).

	Percentage by age-class						
Report period	0	I	II	III	IV	V	Total number
1976-77	4	23	29	26	13	5	698
1977-78	8	20	22	23	17	10	516
1978-79	6	20	25	25	13	11	357
1979-80	4	36	31	17	8	4	927
1980-81	11	37	33	16	7	6	779
1981-82	32	18	21	17	6	6	617
1982-83	24	18	21	20	8	9	477
1983-84	25	22	20	16	7	7	231
1984-85	21	27	12	16	9	14	164
1985-86	12	29	20	16	10	14	51
1986-87	83	7	0	2	4	4	53

[a]Length-age key from Serchuck (1972)

Data collected at SNPS were examined to determine if trends in cunner abundance were similar

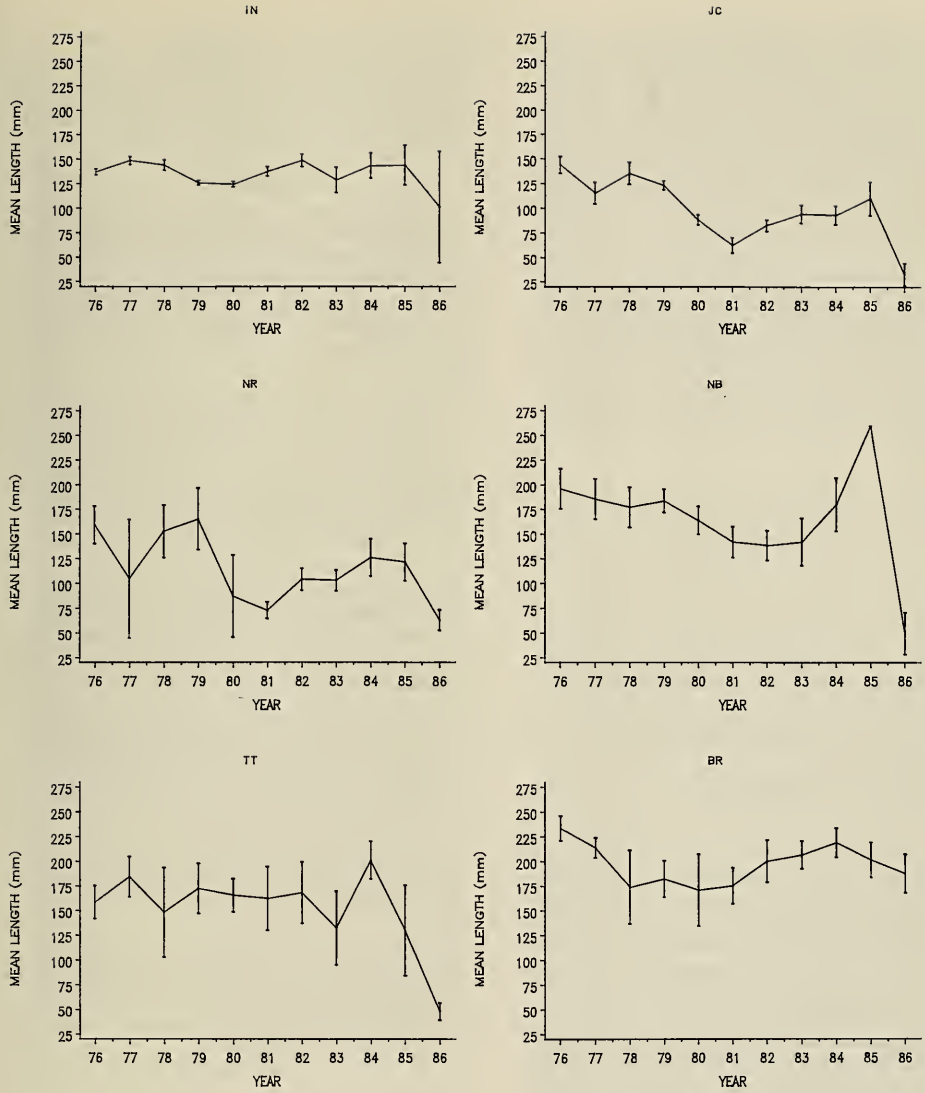

Fig. 14. The annual mean length and 95% confidence interval of cunner taken by trawl at each station.

to the Millstone area (Table 31). Larval to egg ratios were also low indicating poor egg survival. The egg abundance index at SNPS in 1986 was the lowest compared to other years, but the estimated annual abundance fluctuated much more than at Millstone. Larval abundance did not decline at SNPS in recent years as it has here, but similar to Millstone, some of the lowest catches by trawl at SNPS occurred in 1985 and 1986.

TABLE 31. Annual abundance indices of cunner eggs and larvae, both expressed as an annual sum of means, and trawl catch as annual CPUE at Shoreham Nuclear Power Station.

Year	Sum[a] eggs	Sum[a] larvae	Trawl CPUE
1977	8119	1064	0.07
1978	4706	307	0.14
1979	14225	308	0.51
1980	3848	42	0.68
1981	3587	43	0.25
1982	2367	–[b]	0.09
1983	9221	151	0.27
1984	9724	64	0.52
1985	2429	156	0.08
1986	1454	487	0.07

[a]Sums for 1977-82 based on mean density per sampling trip (Geomet Tech. 1983) and for 1983-86 based on monthly mean density (EA Eng., Sci., and Tech. 1987).

[b]Abundance not reported (Geomet Tech. 1983) apparently due to low densities.

In summary, the abundance of all life history stages of cunner at stations close to MNPS has recently declined. The decrease in impingement can, in part, be attributed to an overall decline in impingement at Unit 2 since the start-up of Unit 3, but also may be related to an apparent decrease in the cunner population near MNPS. Some of the decline of juveniles and adults was likely the result of several changes in physical habitat near IN trawl station. Concurrent with the decrease in trawl catch was a reduction in mean length. If changes in juvenile and adult abundance were related to entrainment losses, then juvenile recruitment would decrease and cause the mean length to increase. The cause of the change in the cunner population is not known, and monitoring of its abundance will continue to determine if the decrease was a result of natural long-term fluctuations or the operation of MNPS.

Conclusions

The life history stages of fishes collected in the fish ecology programs were examined to determine which species were most susceptible to potential impact due to the operation of MNPS, with particular emphasis on the period of three-unit operations. There was a significant decrease in the total impingement at Unit 2 starting with the removal of the Unit 3 cofferdam in the summer of 1983 and a continuing decline through 1987, possibly due to a change in water circulation patterns with the start-up of Unit 3. Because the objectives of the impingement program were completed, Unit 2 impingement monitoring was discontinued on December 11, 1987.

Eight taxa were selected for detailed examination: American sand lance, anchovies, sticklebacks, Atlantic tomcod, silversides, grubby, tautog, and cunner. There was no apparent change in the distribution or abundance of the silversides in Jordan Cove related to the increased thermal plume with three-unit operations. As expected, increased cooling water demands of three-unit operations increased annual entrainment estimates for most of the abundant ichthyoplankton taxa. The sand lance and cunner were the only taxa that showed a decline concurrent with three-unit operations. The decrease in sand lance larvae has been occurring throughout the 1980s and was attributed to a regional decline in adults. The cause for the cunner decline was not ascertained, but monitoring will continue to determine if the decrease was due to natural long-term fluctuations or the operation of MNPS.

Summary

1. The operation of MNPS could affect fish assemblages in the Millstone area in several ways. Juveniles and adults could be lost due to impingement on the intake screens. The mortality rates of early history stages could be increased by entraining eggs and larvae through the condenser cooling water system. The local distributions could be altered by the thermal plume. This report emphasizes the comparison of data collected during two-unit operations to those collected since the start-up of Unit 3.

2. Impingement monitoring at Unit 2 was discontinued on December 11, 1987 because losses have been well-documented and all feasible mitigative measures have been investigated. There was a significant decline in total impingement in recent years, which was attributed to physical changes near the Unit 2 intake and possible changes in water circulation patterns because of the operation of Unit 3. Losses due to impingement by MNPS were reduced with the installation of fish return sluiceways at Units 1 and 3.

3. Over 100 fish taxa have been collected in the monitoring programs since 1976. These programs were demersal trawl, shore-zone seine, impingement, and ichthyoplankton. Eight taxa were selected for detailed examination due to their prevalence in entrainment or impingement collections or their abundance in the shore-zone area of Jordan Cove, an area which may be impacted by the thermal plume.

4. The American sand lance was primarily collected as larvae and was a dominant entrained taxon. A decline in larval abundance since the early 1980s was attributed to a regional decrease in adult stock size.

5. Several life history stages of anchovies were very abundant in some sampling programs. Adults were present in impingement collections, juveniles were caught by trawl, and eggs and larvae were abundant in entrainment samples. The numbers impinged have declined in recent years. Comparison of annual egg and larval abundance indices suggested compensatory mortality during the early life history stages, which could help mitigate losses due to entrainment.

6. Sticklebacks and Atlantic tomcod were primarily found in impingement collections. The impact of MNPS impingement on sticklebacks has been reduced due to high ($>70\%$) survival of individuals returned by sluiceways at Units 1 and 3. There was a marked decrease in Atlantic tomcod numbers impinged at Unit 2 since the start-up of Unit 3.

7. Silversides dominated the shore-zone area of Jordan Cove and adults were abundant in winter trawl and impingement collections. There was a recent decline in the number impinged at Unit 2, but this was not evident in the number caught by trawl. There were no apparent changes in length-frequency distribution or seasonal abundance in Jordan Cove related to the three-unit thermal plume.

8. Grubby larvae were present in ichthyoplankton collections and juveniles and adults were present in trawl and impingement collections. Larval abundance has declined in recent years to levels similar to the late 1970s. Numbers impinged at Unit 2 have decreased and those returned by the Units 1 and 3 sluiceways had high survival ($>74\%$). Except for station NR, there has been no long-term changes in the mean length or abundance indices of adults collected by trawl.

9. The tautog is an important recreational fish in the Millstone area and the greatest potential impact of MNPS on it is through the entrainment of eggs. Egg abundance, the best index of adult stock size, has increased in recent years, but larval densities declined to levels similar to the late 1970s. There was

an apparent poor egg to larval survival in all years examined, with the lowest during recent years. Because the tautog takes 2 to 4 years to reach maturity, the possible impact of entrainment by three-unit operations on adult stock size will not be evident for several years.

10. The abundances of all life history stages of cunner collected near MNPS have recently declined. Decreased impingement was attributed, in part, to the overall decline in total impingement at Unit 2. Decreases in the trawl catch were evident at stations closest to MNPS. Part of the decreasing trend in juvenile and adult abundance at station IN could have been caused by physical changes to the habitat, but reasons for the decline at other stations are not known. In 1986, the abundance of eggs and larvae were among the lowest found since 1976. There was an apparent low egg to larval survival for all years examined, and, similar to tautog, poorest survival occurred in recent years. In addition, there were similar fluctuations in the annual abundance of cunner and tautog larvae, suggesting that factors affecting the survival of early life history stages were similar for both species. Further monitoring will continue to determine if the apparent decrease in the cunner population was a result of natural long-term fluctuations or from the operation of MNPS.

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Appendices to Fish Ecology Studies

APPENDIX I. List of fishes collected in the Fish Ecology sampling programs.

Scientific name	Common name	Trawl	Seine	Impingement	Ichthyoplankton
Acipenser oxyrhynchus	Atlantic sturgeon	*			
Alectis ciliaris	African pompano			*	
Alosa aestivalis	blueback herring	*	*	*	
Alosa mediocris	hickory shad	*		*	
Alosa pseudoharengus	alewife	*	*	*	*
Alosa sapidissima	American shad	*	*	*	
Alosa spp.	alosid	*	*	*	*
Aluterus schoepfi	orange filefish	*		*	
Ammodytes americanus	American sand lance	*	*	*	*
Anchoa hepsetus	striped anchovy			*	*
Anchoa mitchilli	bay anchovy	*	*	*	*
Anguilla rostrata	American eel	*	*	*	*
Apeltes quadracus	fourspine stickleback	*	*	*	*
Aulostomus maculatus	trumpetfish			*	
Bairdiella chrysoura	silver perch	*		*	
Bothidae	left-eye flounder				*
Brevoortia tyrannus	Atlantic menhaden	*	*	*	*
Brosme brosme	cusk	*		*	
Caranx crysos	blue runner	*	*	*	
Caranx hippos	crevalle jack	*	*	*	
Centropristis striata	black sea bass	*		*	*
Chaetodon ocellatus	spotfin butterflyfish	*		*	*
Chilomycterus schoepfi	striped burrfish			*	
Clupeidae	herrings	*		*	*
Clupea harengus	Atlantic herring	*	*	*	*
Conger oceanicus	conger eel	*		*	*
Cyclopterus lumpus	lumpfish	*		*	*
Cynoscion regalis	weakfish	*	*	*	*
Cyprinodon variegatus	sheepshead minnow		*	*	*
Dactylopterus volitans	flying gurnard	*		*	
Dasyatis centroura	roughtail sting-ray	*			
Decapterus macarellus	mackerel scad	*		*	
Enchelyopus cimbrius	fourbeard rockling	*		*	*
Etropus microstomus	smallmouth flounder	*		*	*
Eucinostomus lefroyi	mottled mojarra		*		
Fistularia tabacaria	bluespotted cornetfish	*		*	
Fundulus diaphanus	banded killifish		*		
Fundulus heteroclitus	mummichog	*	*	*	
Fundulus luciae	spotfin killifish		*		
Fundulus majalis	striped killifish		*	*	

APPENDIX I continued.

Scientific name	Common name	Trawl	Seine	Impingement	Icthyoplankton
Gadidae	codfishes	*	*	*	*
Gadus morhua	Atlantic cod	*		*	*
Gasterosteus aculeatus	threespine stickleback	*	*	*	*
Gasterosteus wheatlandi	blackspotted stickleback	*	*	*	*
Gobiidae	gobies	*			*
Gobiosoma ginsburgi	seaboard goby	*			
Hemitripterus americanus	sea raven	*		*	*
Hippocampus erectus	lined seahorse	*		*	*
Labridae	wrasses				*
Lactophrys spp.	boxfish	*			
Leiostomus xanthurus	spot	*		*	
Liparis spp.	seasnail	*		*	*
Lophius americanus	goosefish	*		*	*
Lucania parva	rainwater killifish	*	*		
Lumpenus lumpretaeformis	snakeblenny				*
Macrozoarces americanus	ocean pout	*		*	
Melanogrammus aeglefinus	haddock	*		*	
Menticirrhus saxatilis	northern kingfish	*	*	*	*
Menidia beryllina	inland silverside	*	*	*	
Menidia menidia	Atlantic silverside	*	*	*	*
Merluccius bilinearis	silver hake	*	*	*	*
Microgadus tomcod	Atlantic tomcod	*		*	*
Monacanthus hispidus	planehead filefish	*		*	
Monocanthus spp.	filefish	*		*	
Morone americana	white perch	*		*	*
Morone saxatilis	striped bass	*	*	*	
Mugil cephalus	striped mullet	*	*	*	*
Mugil curema	white mullet		*	*	
Mullus auratus	red goatfish	*			
Mustelis canis	smooth dogfish	*		*	
Myliobatis freminvillei	bullnose ray	*			
Myoxocephalus aenaeus	grubby	*	*	*	*
Myoxocephalus octodecemspinosus	longhorn sculpin	*		*	*
Myoxocephalus spp.	sculpin	*		*	
Ophidiidae	cusk-eels	*		*	
Ophidion marginatum	striped cusk-eel	*	*	*	*
Ophidion welshi	crested cusk-eel			*	
Opsanus tau	oyster toadfish	*		*	
Osmerus mordax	rainbow smelt	*	*	*	*

APPENDIX 1 continued.

Scientific name	Common name	Trawl	Seine	Impingement	Ichthyoplankton
Paralichthys dentatus	summer flounder	*		*	*
Paralichthys oblongus	fourspot flounder	*		*	*
Peprilus triacanthus	butterfish	*	*	*	*
Petromyon marinus	sea lamprey			*	
Pholis gunnellus	rock gunnell	*	*	*	*
Pollachius virens	pollock	*		*	*
Pomatomus saltatrix	bluefish	*	*	*	
Priacanthus arenatus	bigeye	*		*	
Priacanthus cruentatus	glasseye snapper	*		*	
Pristigenys alta	short bigeye	*		*	
Prionotus carolinus	northern scarobin	*	*	*	*
Prionotus evolans	striped searobin	*	*	*	*
Pseudopleuronectes americanus	winter flounder	*	*	*	*
Pungitius pungitius	ninespine stickleback	*	*	*	*
Raja eglanteria	clearnose skate	*			
Raja erinacea	little skate	*		*	
Raja ocellata	winter skate	*		*	
Salmo trutta	brown trout	*		*	
Sciaenidae	drums				*
Scophthalmus aquosus	windowpane	*	*	*	*
Scomber scombrus	Atlantic mackerel	*		*	*
Scyliorhinus retifer	chain dogfish	*			
Selar crumenopthalmus	bigeye scad	*		*	
Selene setapinnis	Atlantic moonfish	*		*	
Selene vomer	lookdown	*	*	*	
Seriola zonata	banded rudderfish			*	
Synodus foetens	inshore lizardfish	*			
Sphyraena borealis	northern sennet	*		*	
Sphoeroides maculatus	northern puffer	*	*	*	*
Squalus acanthias	spiny dogfish	*		*	
Stenotomus chrysops	scup	*		*	*
Strongylura marina	Atlantic needlefish		*		
Syngnathus fuscus	northern pipefish	*	*	*	*
Tautogolabrus adspersus	cunner	*	*	*	*
Tautoga onitis	tautog	*	*	*	*
Trachinotus falcatus	permit	*	*		
Trachurus lathami	rough scad	*		*	
Trachinocephalus myops	snakefish	*			

APPENDIX I continued.

Scientific name	Common name	Trawl	Seine	Impingement	Icthyoplankton
Trinectes maculatus	hogchoker	*		*	
Ulvaria subbifurcata	radiated shanny	*		*	*
Upeneus parvus	dwarf goatfish	*			
Urophycis chuss	red hake	*	*	*	
Urophycis tenuis	white hake	*	*	*	
Urophycis spp.	hake	*	*	*	*

APPENDIX II. Total trawl catch of fish taxa and number of samples collected by report period (June-May).

Taxon	76-77	77-78	78-79	79-80	80-81	81-82	82-83	83-84	84-85	85-86	86-87	Total
Number of samples	468	468	468	468	468	468	473	477	468	468	468	5162
Pseudopleuronectes americanus	7415	6045	7236	11442	13296	10749	19201	12560	13260	9849	9321	120374
Stenotomus chrysops	1918	4040	2556	4094	3844	3403	4896	5268	4206	2640	5205	42070
Anchoa spp.	979	580	2226	16	109	578	38	109	157	10003	8038	22833
Scophthalmus aquosus	1480	1296	875	1508	2016	1518	3517	2475	2199	2483	1655	21022
Raja spp.	661	579	362	402	954	696	2797	2493	1583	3801	2207	16535
Menidia spp.	2152	1647	1463	1340	882	501	518	583	322	519	3438	13365
Gadidae	112	326	230	211	3296	1424	476	481	562	630	168	7916
Tautogolabrus adspersus	838	875	400	1399	940	840	611	362	248	119	147	6779
Myoxocephalus aenaeus	266	636	297	342	632	870	996	672	477	341	727	6256
Prionotus spp.	338	322	138	313	405	661	1059	422	371	395	436	4860
Paralichthys dentatus	286	141	92	75	122	240	250	269	1937	281	653	4346
Merluccius bilinearis	425	163	69	134	558	220	382	147	100	175	197	2570
Urophycis spp.	99	87	103	69	163	313	615	286	251	272	286	2544
Gasterosteus aculeatus	30	12	47	77	206	103	63	218	1102	116	354	2328
Tautoga onitis	229	283	263	270	146	228	239	140	119	134	215	2266
Hemitripterus americanus	34	48	39	148	278	410	557	377	125	41	45	2102
Pholis gunnellus	85	106	99	65	251	273	302	145	127	151	186	1790
Syngnathus fuscus	43	54	49	88	151	264	232	202	254	196	207	1740
Osmerus mordax	111	286	90	5	123	63	89	26	227	391	257	1668
Peprilus triacanthus	37	44	407	174	44	69	182	244	19	135	132	1487
Apeltes quadracus	10	6	24	27	194	765	76	11	112	130	107	1462
Etropus microstomus	43	7	0	3	31	91	94	56	85	218	640	1268
Centropristis striata	33	9	3	4	10	63	23	38	30	80	412	705
Myoxocephalus octodecemspinosus	11	10	97	40	30	145	172	51	20	13	12	601
Alosa pseudoharengus	11	272	13	17	4	15	5	26	4	16	208	591
Paralichthys oblongus	31	7	21	11	51	32	138	34	81	66	72	544
Ammodytes americanus	5	59	128	36	117	14	19	11	19	6	11	425
Opsanus tau	98	21	7	18	31	35	25	23	24	32	56	370
Anguilla rostrata	19	16	8	5	10	37	29	24	22	34	28	232
Cyclopterus lumpus	19	11	28	58	11	0	14	1	29	1	1	173
Liparis spp.	9	27	10	10	18	33	15	16	11	3	18	170
Cynoscion regalis	9	21	4	2	2	45	7	0	1	5	36	132
Alosa sapidissima	33	6	1	5	40	12	0	29	0	0	1	127
Clupeidae	2	1	0	0	0	0	0	0	0	110	0	113
Clupea harengus	1	9	13	0	0	1	0	2	9	63	10	108
Sphoeroides maculatus	16	10	1	0	9	14	16	15	7	7	3	98

APPENDIX II continued.

Taxon	76-77	77-78	78-79	79-80	80-81	81-82	82-83	83-84	84-85	85-86	86-87	Total
Mustelis canis	2	5	45	11	1	5	4	6	0	2	2	83
Brevoortia tyrannus	1	14	11	1	1	1	0	1	0	34	10	74
Alosa aestivalis	3	11	8	12	4	1	1	17	5	2	4	68
Monacanthus hispidus	3	6	8	4	0	0	8	1	8	9	2	49
Limanda ferruginea	7	5	5	2	3	15	6	0	4	0	0	47
Morone americana	8	17	3	5	8	2	1	0	0	0	0	44
Macrozoarces americanus	5	7	9	2	2	2	2	2	3	1	0	35
Hippocampus spp.	0	0	0	0	0	0	0	1	4	7	20	32
Gobiidae	3	0	0	0	4	0	0	3	9	7	2	28
Fistularia tabacaria	2	3	0	0	3	0	1	0	8	1	2	20
Leiostomus xanthurus	5	6	0	0	0	0	2	0	0	3	1	17
Pungitius pungitius	0	0	0	0	1	2	0	0	5	1	5	14
Gasterosteidae	0	0	0	13	0	0	0	0	0	0	0	13
Pomatomus saltatrix	1	1	0	2	1	2	3	3	0	0	0	13
Aluterus schoepfi	0	2	2	1	1	0	0	1	1	2	2	12
Dactylopterus volitans	3	0	0	0	0	1	3	1	0	1	3	12
Fundulus spp.	0	0	0	0	0	5	2	0	0	2	1	10
Menticirrhus saxatilis	0	1	0	1	0	3	1	0	0	0	4	10
Synodus foetens	0	1	4	0	0	3	1	0	0	0	0	9
Ophidion marginatum	0	0	0	0	0	0	0	0	1	2	4	7
Priacanthus cruentatus	0	0	0	0	0	1	0	2	3	1	0	7
Trinectes maculatus	3	1	0	0	0	0	0	0	0	1	2	7
Gasterosteus wheatlandi	0	0	0	0	0	1	1	1	0	1	2	6
Lophius americanus	2	0	0	0	1	0	1	1	0	0	1	6
Morone saxatilis	0	0	2	1	0	1	1	0	0	1	0	6
Ulvaria subbifurcata	0	2	0	0	1	1	0	0	0	1	1	6
Caranx crysos	0	0	0	0	1	0	1	0	1	2	0	5
Conger oceanicus	1	0	0	0	1	0	0	0	2	0	1	5
Pristigenys alta	0	0	0	0	0	1	0	0	2	1	1	5
Mullus auratus	0	0	1	0	0	0	2	0	0	0	1	4
Selene vomer	1	2	0	0	0	0	0	0	0	0	1	4
Sphyraena borealis	0	0	0	0	0	0	0	1	1	2	0	4
Trachurus lathami	0	0	0	4	0	0	0	0	0	0	0	4
Chaetodon ocellatus	0	0	0	0	1	0	0	1	0	0	1	3
Lactophrys spp.	0	0	0	0	0	0	0	0	3	0	0	3
Mugil cephalus	0	0	0	0	0	0	1	0	0	2	0	3
Priacanthus arenatus	0	0	0	0	0	0	0	0	2	1	0	3
Alosa mediocris	1	0	0	0	1	0	0	0	0	0	0	2

APPENDIX II continued.

Taxon	76-77	77-78	78-79	79-80	80-81	81-82	82-83	83-84	84-85	85-86	86-87	Total
Caranx hippos	0	0	0	0	0	0	1	0	0	1	0	2
Decapterus macarellus	0	0	0	0	0	0	0	0	2	0	0	2
Enchelyopus cimbrius	0	0	0	0	0	1	0	0	0	0	1	2
Scomber scombrus	0	1	0	1	0	0	0	0	0	0	0	2
Squalus acanthias	0	0	0	0	0	0	1	0	1	0	0	2
Acipenser oxyrhynchus	0	0	0	1	0	0	0	0	0	0	0	1
Aulostomus maculatus	1	0	0	0	0	0	0	0	0	0	0	1
Bairdiella chrysoura	0	0	0	0	0	0	0	1	0	0	0	1
Bothus ocellatus	0	0	0	0	0	0	1	0	0	0	0	1
Dasyatis centroura	0	0	0	0	0	0	0	0	1	0	0	1
Melanogrammus aeglefinus	0	0	0	0	0	0	0	1	0	0	0	1
Monocanthus spp.	0	0	0	0	0	0	0	0	0	0	1	1
Myliobatis freminvillei	0	0	0	0	0	0	1	0	0	0	0	1
Myoxocephalus spp.	0	0	0	0	0	0	0	0	0	0	1	1
Ophidiidae	0	0	0	0	0	0	0	0	0	0	1	1
Salmo trutta	0	0	0	0	1	0	0	0	0	0	0	1
Scyliorhinus retifer	1	0	0	0	0	0	0	0	0	0	0	1
Selar crumenopthalmus	0	0	0	0	0	0	0	0	0	1	0	1
Selene setapinnis	0	0	0	0	0	0	0	0	1	0	0	1
Trachinocephalus myops	0	0	0	0	0	0	0	0	1	0	0	1
Trachinotus falcatus	0	0	0	0	0	0	0	0	1	0	0	1
Upeneus parvus	0	0	0	0	0	0	0	0	0	1	0	1
Total	17941	18147	17497	22469	29010	24773	37699	27860	28169	33546	35566	292677

APPENDIX III. Total trawl catch of fish and the number of samples collected by station.

Taxon	JC	NR	NB	TT	BR	IN	Total
Number of samples	861	861	861	860	858	861	5162
Pseudopleuronectes americanus	11591	38093	17033	19956	14873	18828	120374
Stenotomus chrysops	3015	239	17398	6543	3739	11136	42070
Anchoa spp.	1004	249	17914	295	16	3355	22833
Scophthalmus aquosus	1199	1742	1888	2828	10931	2434	21022
Raja spp.	797	9	2734	4433	6643	1919	16535
Menidia spp.	3721	3950	1438	656	184	3416	13365
Gadidae	1777	719	2632	998	242	1548	7916
Tautogolabrus adspersus	1404	321	490	249	443	3872	6779
Myoxocephalus aenaeus	919	2614	354	394	666	1309	6256
Prionotus spp.	82	444	374	964	2439	557	4860
Paralichthys dentatus	649	830	529	1642	167	529	4346
Merluccius bilinearis	142	3	376	316	1224	509	2570
Urophycis spp.	306	28	247	237	1377	349	2544
Gasterosteus aculeatus	1599	700	9	6	6	8	2328
Tautoga onitis	493	533	253	177	242	568	2266
Hemitripterus americanus	442	82	401	294	484	399	2102
Pholis gunnellus	958	208	217	109	19	279	1790
Syngnathus fuscus	518	827	112	65	74	144	1740
Osmerus mordax	1082	237	111	71	59	108	1668
Peprilus triacanthus	24	3	202	409	790	59	1487
Apeltes quadracus	133	1324	1	1	1	2	1462
Etropus microstomus	94	9	282	127	558	198	1268
Centropristis striata	66	147	33	30	26	403	705
Myoxocephalus octodecemspinosus	3	0	20	52	511	15	601
Alosa pseudoharengus	7	63	19	12	250	240	591
Paralichthys oblongus	0	2	59	6	453	24	544
Ammodytes americanus	19	94	5	29	269	9	425
Opsanus tau	6	353	0	0	0	11	370
Anguilla rostrata	35	173	0	16	2	6	232
Cyclopterus lumpus	107	4	11	6	2	43	173
Liparis spp.	19	1	34	28	65	23	170
Cynoscion regalis	20	0	24	10	59	19	132
Alosa sapidissima	8	17	51	9	20	22	127
Clupeidae	0	1	0	1	0	111	113
Clupea harengus	63	4	13	9	15	4	108
Sphoeroides maculatus	11	57	9	2	12	7	98

APPENDIX III continued.

Taxon	JC	NR	NB	TT	BR	IN	Total
Mustelis canis	4	1	39	3	32	4	83
Brevoortia tyrannus	0	58	12	1	0	3	74
Alosa aestivalis	1	20	14	7	14	12	68
Monacanthus hispidus	16	1	7	5	11	9	49
Limanda ferruginea	0	0	0	4	43	0	47
Morone americana	6	11	4	1	5	17	44
Macrozoarces americanus	0	0	0	1	33	1	35
Hippocampus spp.	12	13	1	2	1	3	32
Gobiidae	2	26	0	0	0	0	28
Fistularia tabacaria	16	1	0	0	0	3	20
Leiostomus xanthurus	2	0	8	0	4	3	17
Pungitius pungitius	10	3	0	0	0	1	14
Gasterosteidae	2	11	.	.	.	.	13
Pomatomus saltatrix	2	3	2	0	5	1	13
Aluterus schoepfi	6	0	0	2	1	3	12
Dactylopterus volitans	1	8	0	0	0	3	12
Fundulus spp.	1	9	0	0	0	0	10
Menticirrhus saxatilis	0	2	3	3	0	2	10
Synodus foetens	0	3	0	2	4	0	9
Ophidion marginatum	0	0	1	2	4	0	7
Priacanthus cruentatus	1	0	1	2	0	3	7
Trinectes maculatus	5	1	0	0	0	1	7
Gasterosteus wheatlandi	6	.	.	.	.	.	6
Lophius americanus	0	0	1	1	4	0	6
Morone saxatilis	0	6	0	0	0	0	6
Ulvaria subbifurcata	3	0	0	1	1	1	6
Caranx crysos	0	0	2	0	1	2	5
Conger oceanicus	1	1	1	0	2	0	5
Pristigenys alta	2	0	0	1	1	1	5
Mullus auratus	1	0	0	0	0	3	4
Selene vomer	1	0	2	0	0	1	4
Sphyraena borealis	4	0	0	0	0	0	4
Trachurus lathami	1	0	3	0	0	0	4
Chaetodon ocellatus	2	1	0	0	0	0	3
Lactophrys spp.	2	1	0	0	0	0	3
Mugil cephalus	1	1	1	0	0	0	3
Priacanthus arenatus	0	1	0	0	0	2	3
Alosa mediocris	1	0	0	0	1	0	2

APPENDIX III continued.

Taxon	JC	NR	NB	TT	BR	IN	Total
Caranx hippos	0	0	0	0	0	2	2
Decapterus macarellus	1	0	1	0	0	0	2
Enchelyopus cimbrius	0	0	0	0	2	0	2
Scomber scombrus	0	0	1	0	0	1	2
Squalus acanthias	0	0	0	0	2	0	2
Acipenser oxyrhynchus	0	0	1	0	0	0	1
Aulostomus maculatus	1	0	0	0	0	0	1
Bairdiella chrysoura	0	0	0	0	1	0	1
Bothus ocellatus	0	1	0	0	0	0	1
Dasyatis centroura	1	0	0	0	0	0	1
Melanogrammus aeglefinus	1	0	0	0	0	0	1
Monocanthus spp.	1	0	0	0	0	0	1
Myliobatis freminvillei	0	0	1	0	0	0	1
Myoxocephalus spp.	0	1	0	0	0	0	1
Ophidiidae	0	0	0	0	1	0	1
Salmo trutta	0	1	0	0	0	0	1
Scyliorhinus retifer	0	1	0	0	0	0	1
Selar crumenopthalmus	0	0	0	1	0	0	1
Selene setapinnis	0	0	1	0	0	0	1
Trachinocephalus myops	1	0	0	0	0	0	1
Trachinotus falcatus	0	0	0	0	0	1	1
Upeneus parvus	1	0	0	0	0	0	1
Total	32432	54266	65380	41019	47034	52546	292677

APPENDIX IV. Total seine catch of fish taxa and number of samples collected by report period (June-May).

Taxon	76-77	77-78	78-79	79-80	80-81	81-82	82-83	83-84	84-85	85-86	86-87	Total
Number of samples	66	72	72	72	72	72	98	120	174	156	156	1130
Menidia spp.	40619	18194	1335	1062	7996	3186	5413	9807	1538	1375	5441	95966
Fundulus spp.	1695	1199	815	659	952	613	915	1081	1463	906	111	10409
Apeltes quadracus	464	603	258	266	49	94	89	1827	167	106	297	4220
Cyprinodon variegatus	48	673	39	30	10	352	146	50	29	28	2	1407
Ammodytes americanus	6	520	16	51	10	318	82	30	21	0	7	1061
Pungitius pungitius	5	1	28	2	5	2	10	321	8	11	8	401
Gasterosteus aculeatus	9	154	27	5	3	2	5	53	6	6	19	289
Syngnathus fuscus	9	3	9	108	6	8	21	12	35	30	33	274
Pomatomus saltatrix	1	0	1	6	0	2	135	4	19	35	12	215
Mugil cephalus	0	4	3	23	41	1	4	4	1	0	38	119
Pseudopleuronectes americanus	4	6	4	1	6	5	2	3	17	40	18	106
Gadidae	2	0	9	2	20	16	11	8	11	11	8	98
Alosa pseudoharengus	0	0	0	0	0	0	0	1	93	0	0	94
Gasterosteus wheatlandi	.	.	.	.	.	8	6	6	19	12	9	60
Brevoortia tyrannus	0	0	17	0	4	0	7	1	0	8	6	43
Anguilla rostrata	10	5	12	3	2	0	1	1	0	0	3	37
Clupea harengus	0	0	0	0	0	0	2	0	0	0	30	32
Myoxocephalus aenaeus	3	2	1	2	0	0	3	1	3	3	3	21
Anchoa spp.	0	0	0	0	2	0	7	2	1	0	0	12
Gasterosteus spp.	.	.	.	.	.	.	.	.	.	.	12	12
Mugil curema	0	0	0	0	0	0	0	1	9	0	0	10
Alosa aestivalis	2	6	0	0	0	0	0	0	0	0	0	8
Sphoeroides maculatus	0	0	0	1	0	0	1	0	0	3	3	8
Lucania parva	1	2	0	0	0	0	0	2	0	1	0	6
Tautogolabrus adspersus	0	0	2	0	0	0	3	0	1	0	0	6
Tautoga onitis	0	0	0	0	0	0	4	0	0	0	0	4
Trachinotus falcatus	0	0	1	0	3	0	0	0	0	0	0	4
Caranx hippos	0	0	1	0	0	1	0	0	0	1	0	3
Alosa sapidissima	1	0	0	0	0	0	0	0	0	1	0	2
Menticirrhus saxatilis	1	0	1	0	0	0	0	0	0	0	0	2
Osmerus mordax	0	0	0	0	0	0	0	0	0	2	0	2
Peprilus triacanthus	0	0	0	0	0	0	1	0	1	0	0	2
Pholis gunnellus	0	0	0	0	0	0	0	0	0	1	1	2
Strongylura marina	0	0	0	0	0	1	1	0	0	0	0	2
Clupeidae	1	0	0	0	0	0	0	0	0	0	0	1
Cynoscion regalis	0	0	0	0	0	0	0	0	1	0	0	1
Prionotus spp.	0	0	0	0	0	0	0	0	0	1	0	1
Scophthalmus aquosus	0	0	0	0	0	0	0	0	0	1	0	1
Urophycis spp.	0	0	0	0	0	0	0	0	1	0	0	1
Total	42881	21372	2579	2221	9109	4609	6869	13215	3444	2582	6061	114942

APPENDIX V. Total seine catch of fish taxa and number of samples collected by station.

Taxon	JC	WP	GN	Total
Number of samples	345	389	396	1130
Menidia spp.	75911	11439	8616	95966
Fundulus spp.	7807	1513	1089	10409
Apeltes quadracus	4199	6	15	4220
Cyprinodon variegatus	626	758	23	1407
Ammodytes americanus	2	198	861	1061
Pungitius pungitius	330	67	4	401
Gasterosteus aculeatus	241	21	27	289
Syngnathus fuscus	48	39	187	274
Pomatomus saltatrix	141	12	62	215
Mugil cephalus	55	40	24	119
Pseudopleuronectes americanus	25	7	74	106
Gadidae	63	29	6	98
Alosa pseudoharengus	5	89	0	94
Gasterosteus wheatlandi	25	13	22	60
Brevoortia tyrannus	2	6	35	43
Anguilla rostrata	31	2	4	37
Clupea harengus	32	0	0	32
Myoxocephalus aenaeus	6	8	7	21
Anchoa spp.	11	1	0	12
Gasterosteus spp.	.	1	11	12
Mugil curema	10	0	0	10
Alosa aestivalis	1	5	2	8
Sphoeroides maculatus	0	1	7	8
Lucania parva	4	0	2	6
Tautogolabrus adspersus	5	1	0	6
Tautoga onitis	4	0	0	4
Trachinotus falcatus	2	2	0	4
Caranx hippos	2	0	1	3
Alosa sapidissima	0	0	2	2
Menticirrhus saxatilis	1	0	1	2
Osmerus mordax	0	0	2	2
Peprilus triacanthus	0	1	1	2
Pholis gunnellus	0	0	2	2
Strongylura marina	2	0	0	2
Clupeidae	0	1	0	1
Cynoscion regalis	1	0	0	1
Prionotus spp.	0	1	0	1
Scophthalmus aquosus	0	0	1	1
Urophycis spp.	0	1	0	1
Total	89592	14262	11088	114942

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The Usage and Estimation of DELTA Means

Statement of the Problem

The average number of marine organisms caught per tow in trawl surveys, or observed in a sample in other monitoring work involving different sampling schemes, is often used as an index of a species abundance. When large areas are sampled and the target species occupies only a part of the total area, the occurrence of samples with no organisms (i.e., zero observations) is unavoidable. Even in situations where a species is known to be present in the entire area, the occurrence of zero observations in varying proportions is still common. The frequency of zero data is particularly high for mobile organisms such as fish, and for plankton, which generally exhibit a high degree of spatial variability or "patchiness".

The presence of zero observations in monitoring data complicates the data analyses on two accounts. First, zero data are difficult to interpret because they may arise from natural patchiness, low population density, undetected sampling gear problems, and other reasons singly or combined; and second, the presence of zero observations increases both the coefficient of variability (i.e., the variance-to-mean ratio) and the skewness of the data. Because both high variability and high skewness contribute to non-normality in data, estimation methods based on normal theory do not apply. Since logarithmic transformations to correct skewness are not effective when many zero observations are present, the usual approach is to use order statistics such as the sample median and nonparametric variance estimators of unknown power. In extreme cases where over 50% of the data are zeros, the median cannot be used because it would always be zero regardless of obvious differences among samples.

This study addresses the estimation problems described above and suggests the use of the δ-*mean* as a more desirable statistic for describing the relative abundance of marine organisms when large numbers of zero observations are present in the data. The performance of the δ-*mean* relative to three other statistics commonly used to estimate population abundance is investigated through numerical simulation. The results of this simulation also serve to illustrate how the four statistics are affected by the presence of zeros in lognormally distributed data.

The Delta Distribution

The delta distribution first introduced by Aitchison (1955) and later described by Aitchison and Brown (1969), is a generalized form of the lognormal model in which some of the observations may be zeros and the nonzero values follow the lognormal distribution. The latter has two parameters (μ) and (σ^2) which are the mean and variance of the log-transformed observations (Hastings and Peacock 1975). The delta distribution has the same two parameters (μ and σ^2) of the underlying lognormal model, plus a third parameter (δ) which is the proportion of zeros in the data. Thus, the lognormal distribution is a particular case of the delta distribution in which the parameter (δ) is zero (i.e., when the data do not contain zero observations).

Because the abundance of living organisms is the result of an inherently multiplicative process (i.e., the number of female parents times a fecundity rate, times a survival rate), random samples of naturally occurring organisms tend to follow the lognormal distribution (Demetrius 1971). In the case of marine organisms, fish in particular, it has been shown that recruitment variability is generally well described by the lognormal distribution (Hennemuth et al. 1980; Peterman 1981; Hilborn 1985). Therefore, the delta distribution appears particularly well suited to describe the

variability of marine organisms when the data contain zero observations.

The typical lognormal distribution is asymmetric, with a long tail on the right-hand side, and with a population mean that lies to the right of the middle point. Because the distance between the middle point and the mean increases with the variability of the data, the geometric mean or its estimator the sample median are often used to describe central tendency in lognormal data. However, there is no known estimator for the variance of those statistics when the lognormal data contain zeros. The basis for applying the delta distribution to describe the abundance of marine organisms is that, for approximately lognormal data with many zeros, the best estimators of the population mean and its variance are the mean of the delta distribution (*δ-mean*) and its variance (*δ-variance*). Like the sample mean (i.e., the average or arithmetic mean of the sample), the *δ-mean* estimates the population mean rather than the mid-point of the data distribution. Recent applications of the delta distribution to describe the variability of ichthyoplankton and fish in the MARMAP program (National Marine Fisheries Service) have been reported by Pennington (1983, 1986).

Estimation of the *δ-mean* and its variance: The minimum variance unbiased estimator of the *δ-mean* was derived by Aitchison (1955). Its computation in practice is rather involved and it generally requires the use of a computer program to evaluate a series iteratively until enough accuracy is reached. The estimate of the *δ-mean* for a given data collection is computed as:

$$\delta\text{-}mean = \frac{m}{n} \exp(\bar{x})\, G_m(y) , \qquad (1)$$

where m is the number of nonzero values in the data, n is the total number of observations in the data, $\bar{x}$ is the arithmetic mean of the log-transformed nonzero observations, and $G_m(y)$ is a Bessel function that is evaluated as the series:

$$G_m(y) = 1 + \frac{(m-1)\,y}{m} + \frac{(m-1)^3 y^2}{m^2(2!)(m+1)} + \frac{(m-1)^5 y^3}{m^3(3!)(m+1)(m+3)} + \ldots \qquad (2)$$

The constant y in these series is computed as:

$$y = \frac{s^2}{2} , \qquad (3)$$

where s^2 is the sample variance of the log-transformed m nonzero observations. The number of terms needed in the series (Eq. 2) to achieve reasonable accuracy was found to be six to ten, depending on the number of significant digits in the logarithmic mean ($\bar{x}$).

The unbiased estimator of the *δ-mean* variance was also derived by Aitchison (1955). However, for large n and a proportion of zeros (δ) appreciably less than 1.0, Owens and DeRouen (1980) found that the approximate (asymptotic) variance of *δ-mean* given by Aitchison and Brown (1969) was accurate enough and much easier to compute. This simplified estimator is computed as:

$$\delta\text{-}var = \frac{1}{n} \exp(2\bar{x} + s^2)\left\{\delta(1-\delta) + \frac{1}{2}(1-\delta)(2s^2 + s^4)\right\} \qquad (4)$$

for a proportion of zeros

$$\delta = 1 - \frac{m}{n} , \qquad (5)$$

and where m, n, $\bar{x}$, and s^2 are as previously defined for equations 1 through 3.

In applications with actual data it is often of interest to construct confidence intervals for the *δ-mean* estimates. Not knowing the exact statistical distribution of the *δ-mean* as estimated by Eq. 1, it may be reasonable to assume asymptotic normality for this estimator in order to form approximate confidence intervals. Owen and DeRouen (1980) investigated this possibility in a

simulation study and concluded that the estimate of δ-*variance* obtained by Eq. 4 provided quite accurate coverage, in both 95% and 99% confidence intervals, for samples with more than 15 observations. Therefore, an approximate 95% confidence interval for large samples (n > 100) can be constructed as:

$$95\%CI = \delta\text{-}mean \pm 1.96\sqrt{\delta\text{-}variance} \quad (6)$$

For smaller sample sizes (15 < n < 100) the corresponding two-tail t-value ($\alpha = 0.05$) replaces the value of 1.96 above.

Comparison of the δ-*mean* to Other Statistics

A numerical simulation was conducted to compare the δ-*mean* to other statistics often used to describe the abundance of marine organisms at NUEL and elsewhere. The statistics chosen for this study where the sample mean, the sample median and the geometric mean. The properties and common usage of these three statistics are briefly discussed first.

The sample mean: The arithmetic mean of a sample or "sample mean" is the unbiased estimator of the true population mean under normality, but it is biased in the case of non-normal data (specially with small samples). The actual estimator of the population mean has specific forms other than a simple arithmetic mean for each known statistical distribution (e.g., Eq. 1 is the form of the unbiased estimator of the delta-distribution mean). However, the sample mean is generally an acceptable estimator of the population mean for symmetric distributions not far from normal when the sample is large. For lognormal distributions with high variance (i.e., long tails), the sample mean is a poor estimator of the population mean and the standard error of the sample mean underestimates the true variance of the lognormal mean (Stuart and Ord 1987). The reason for this is that both lognormal mean and variance increase exponentially with the variance (σ^2) of the log-transformed data. As σ^2 approaches zero the distribution becomes symmetric and the sample mean, lognormal mean and median coincide (Hastings and Peacock 1975).

The sample median: The median of a sample is the value corresponding to the mid-point of the ranked observations in the sample. Unlike the sample mean, the sample median always estimates the mid-point of a distribution. If the distribution is symmetrical its mean and its median coincide (e.g., the normal distribution). For normally distributed random samples, however, the sample mean is a more accurate or "efficient" estimator of the true mean than the median because the standard error is larger for the median than for the mean (Snedecor and Cochran 1980). For this reason, and also because of the superior statistical properties of the mean, the latter is preferred over the median with symmetrical distributions not far from normal. On the other hand, with data whose distribution is highly skewed, the median should be the preferred statistic because it conforms with the concept of an "average" better than the mean. An additional advantage of the median is that it is not affected by extreme values in the sample (i.e., outliers), whereas the sample mean can be greatly affected, more so in the case of small samples. A final consideration regarding the median is that, for data far from normal, nonparametric confidence intervals and tests to compare medians are readily available. The performance of the median and its confidence interval with lognormal data that contain many zeros had not been reported prior to this study.

The geometric mean: The chief application of the geometric mean lies in lognormally distributed data for which the sample mean is a biased estimator of the lognormal mean and the median has only nonparametric (very conservative) estimators of its variance. Unlike the sample mean, the geometric mean is also an estimator of the middle point of a lognormal distribution because it coincides with the median. In practice, a simple logarithmic transformation of the lognormal data allows the estimation of the logarithmic sample mean and variance which then can be used to estimate the geometric mean and its asymmetric

confidence interval in the original scale. When there are zero observations, however, the data must be rescaled prior to log-transformation (by adding some arbitrary positive value to each observation) and this causes the geometric mean and its confidence interval to become biased. Although no studies have been reported investigating the effect of zero observations on the geometric mean, it seems reasonable to assume that the bias will depend on the choice of the constant added to each observation and that it will increase with the proportion of zeros in the data.

Numerical simulation: The basic premise in this simulation was that, for data with an approximate delta-distribution, the δ-*mean* mean and the sample median were the only correct statistics to estimate the population mean and the mid-point of the distribution, respectively. On the basis of distribution theory it was already known that the sample mean and its variance were biased estimators of the lognormal population mean and its variance, and that the geometric mean was a biased estimator of the middle point of lognormal data with many zeros. Therefore, the purpose of the simulation was to describe the relationships among the four statistics (i.e., their relative locations) and to investigate how their magnitudes and the width of their 95% confidence intervals (95%*CI*) were affected by the presence of zeros in the data and by different amounts of variability.

The data base used in the numerical simulation consisted of three data sets of 100 normal random numbers with identical mean ($\bar{x}$ = 2.00) and increasing variances (s^2 = 0.50, 1.00, and 2.25) so that the CV's would be 25, 50, and 75 %. These data were converted into lognormally distributed data by exponentiation of each observation. Therefore, the three lognormal data sets had identical geometric mean, GM = exp(2) = 7.39, and increasing variabilities: CV = 25%, 50%, and 75% in the logarithmic scale. These CV values roughly corresponded to typical (low, moderate, and high) variabilities encountered in samples of marine organisms in various monitoring programs at NUEL (Table 1).

Table 1. Typical sample size, proportion of zero observations, and variability for data collections from NUEL programs where δ-means have been used.

Monitoring Program	Sample Size (n)	Proportion of Zeros (δ)	Variability (CV)[a]
Fish trawl surveys	≅220 (108 to 480)	≅0.55 (0.2 to 0.9)	≅65% (5 to 300%)
Ichthyoplankton surveys	≅200 (44 to 460)	≅0.35 (0.10 to 0.68)	≅55% (35 to 85%)
Lobster larvae entrainment	≅70 (57 to 86)	≅0.55 (0.49 to 0.60)	≅26% (24 to 28%)
Rocky Shore (% cover)	≅30 (13 to 91)	≅0.35 (0.15 to 0.90)	≅70% (20 to 190%)

[a] Coefficient of variability for log-transformed data.

Finally, the lognormal data were converted into "delta-distributed" data by adding an equal number of zeros to each data set and increasing that number in each of the 15 simulations conducted. The zeros added in these simulation were 5, 10, 15, 20, . . , up to 75, resulting in data sets with 105, 110, 115, ..., 175 observations and 4.8 to 43 % of zeros.

The δ-*mean*, the sample mean, the median, and the geometric mean with their respective standard errors were computed separately for each of the three lognormal data sets prior to adding any zeros, and then recomputed after adding zeros in each of the 15 simulations. The 95%*CI*'s for each statistic were also computed and normalized as the percentage of the statistic value represented by the total width of its confidence interval. The purpose of this normalization was to facilitate the comparison of 95%*CI*'s among simulations and across data sets with different variability. Direct comparison of 95%*CI*'s between statistics, however, can be misleading because the standard errors of the sample and geometric means underestimate the true variance. As a result, the 95%*CI*'s for the sample mean and the geometric mean reflect a coverage which is less than the nominal 95%, whereas the 95%*CI* for the δ-*mean* reflects an accurate coverage and the 95%*CI* for the median is very conservative (i.e., its coverage could be closer to 99% than to 95%). The 95%*CI* of the median was estimated using the two order statistics given by Snedecor and Cochran's (1980) nonparametric formula:

$$\frac{n+1}{2} \pm \frac{1.96\sqrt{n}}{2}, \qquad (7)$$

where n is the sample size (100 to 175 observations in this simulation study).

Simulation results: The simulation results are presented in Figure 1a-1b for low variability data, in Figure 2a-2b for moderate variability, and in Figure 3a-3b for high variability. The magnitudes of the four statistics for each simulation are shown in Figures 1a, 2a, and 3a. Although the biased sample mean and the unbiased δ-*mean* did not coincide, they tracked each other remarkably well over the entire range of zeros and variability simulated. Also the median and geometric mean tracked each other well for moderate and high variance data, but the geometric mean was badly affected by the increasing number of zeros when variability was low. Except for highly variable data, the geometric mean was always smaller than the median (very much so at low variance). This indicates that, in the presence of zeros, the geometric mean is not a reliable estimator of the middle point of the data which is always accurately described by the median. The two estimators of the population mean (i.e., the sample mean and the δ-*mean*), were always located to the right of the middle point of the data (as expected) and the separation increased with the variability in the data. Except for the geometric mean in the case of low variability data, the magnitude of the four statistics declined at similar rates in response to the addition of zeros to the lognormal data.

The relative widths of the 95%*CI* for each statistic are shown in Figures 1b, 2b, and 3b. The 95%*CI* of the δ-*mean* (the only CI known to be accurate for "delta" data) increased with the data variability, but its relative witdth was almost unaffected by the number of zeros in the data. Although the 95%*CI* of the sample mean was also quite insensitive to the number of zeros present, its coverage was not accurate because the sample mean standard error underestimates the true variance. Finally, the 95%*CI*'s of the geometric mean and median were erratic and had very different widths, especially with moderate and high variability. Except at low variability, both 95%*CI*'s were greatly affected by the number of zeros in the data.

In summary, the δ-*mean* and its 95%*CI* behaved predictably and consistently over the ranges of data variability and proportion of zeros simulated. The δ-*mean* increased in magnitude with the data variability and decreased as the proportion of zeros increased. The decrease caused by the presence of zeros was more pronounced when the data had high variability. The relative width of

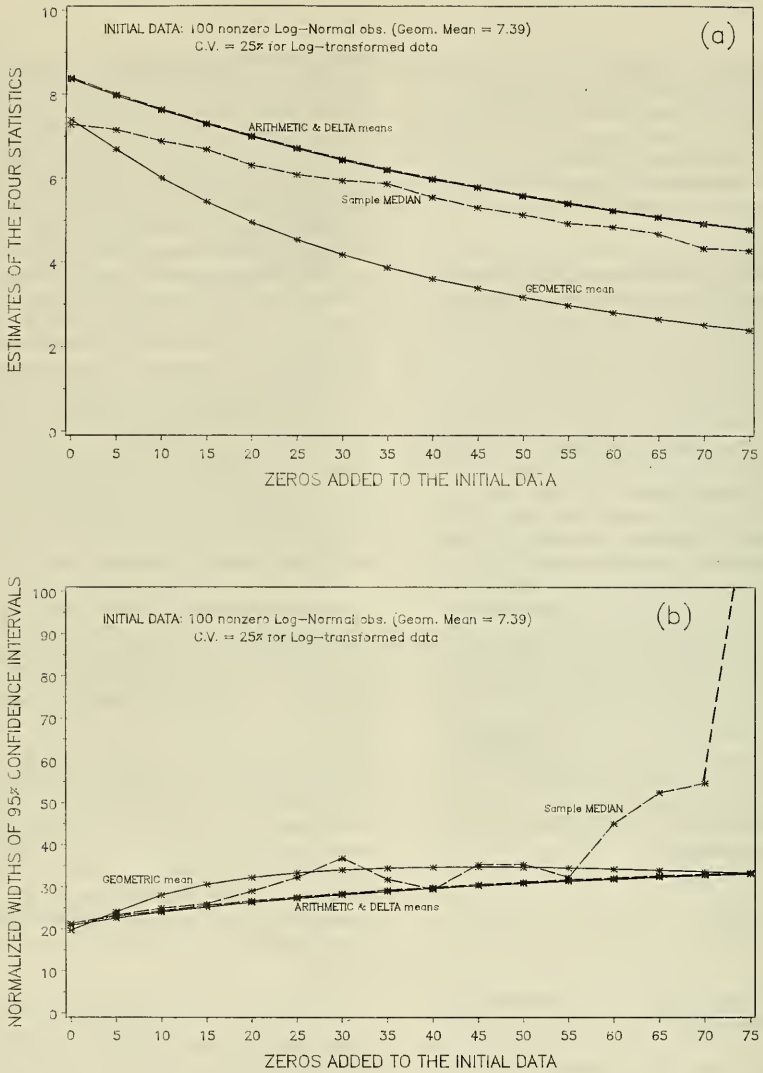
INITIAL DATA: 100 nonzero Log–Normal obs. (Geom. Mean = 7.39)
C.V. = 25% for Log–transformed data
(a)
ARITHMETIC & DELTA means
Sample MEDIAN
GEOMETRIC mean
ESTIMATES OF THE FOUR STATISTICS
ZEROS ADDED TO THE INITIAL DATA
INITIAL DATA: 100 nonzero Log–Normal obs. (Geom. Mean = 7.39)
C.V. = 25% for Log–transformed data
(b)
Sample MEDIAN
GEOMETRIC mean
ARITHMETIC & DELTA means
NORMALIZED WIDTHS OF 95% CONFIDENCE INTERVALS
ZEROS ADDED TO THE INITIAL DATA

Fig. 1 Results of simulating an increasing proportion of zeros in the low-variability data set: a) estimates of the four statistics; b) widths of the 95% *CI*'s normalized as a percentage of the estimated statistics.

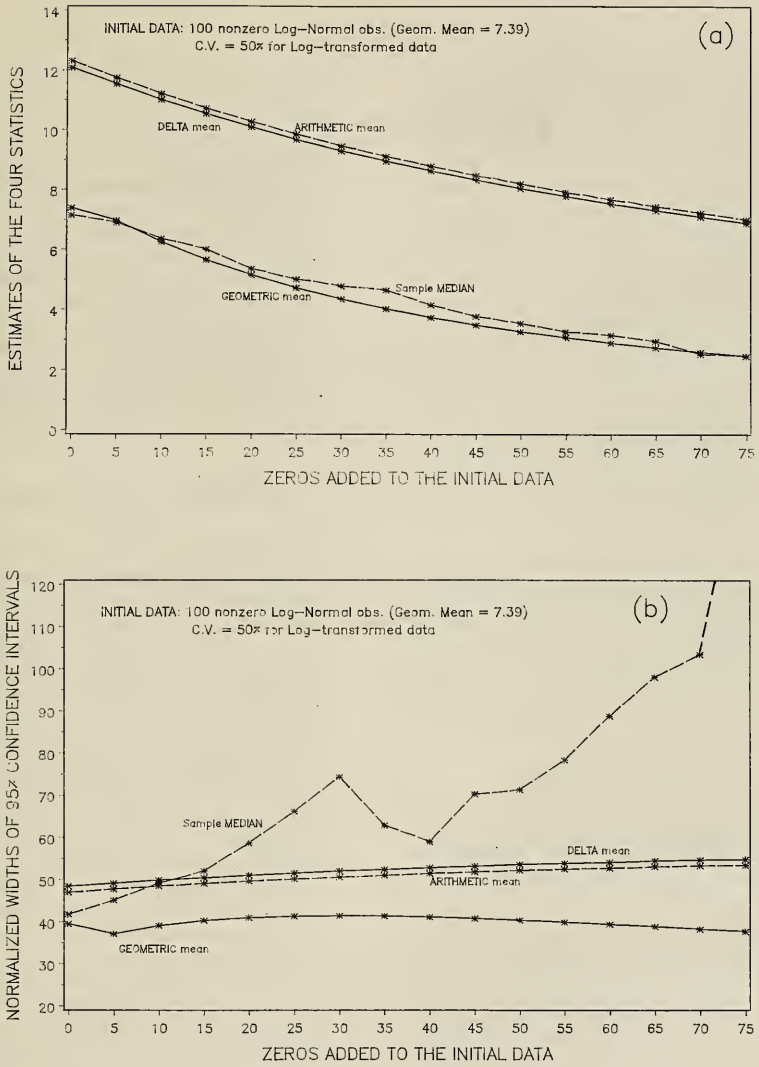
INITIAL DATA: 100 nonzero Log–Normal obs. (Geom. Mean = 7.39)
C.V. = 50% for Log–transformed data
(a)
ESTIMATES OF THE FOUR STATISTICS
DELTA mean
ARITHMETIC mean
Sample MEDIAN
GEOMETRIC mean
ZEROS ADDED TO THE INITIAL DATA
INITIAL DATA: 100 nonzero Log–Normal obs. (Geom. Mean = 7.39)
C.V. = 50% for Log–transformed data
(b)
NORMALIZED WIDTHS OF 95% CONFIDENCE INTERVALS
Sample MEDIAN
DELTA mean
ARITHMETIC mean
GEOMETRIC mean
ZEROS ADDED TO THE INITIAL DATA

Fig. 2 Results of simulating an increasing proportion of zeros in the moderate-variability data set: a) estimates of the four statistics; b) widths of the 95% *CI*'s normalized as a percentage of the estimated statistics.

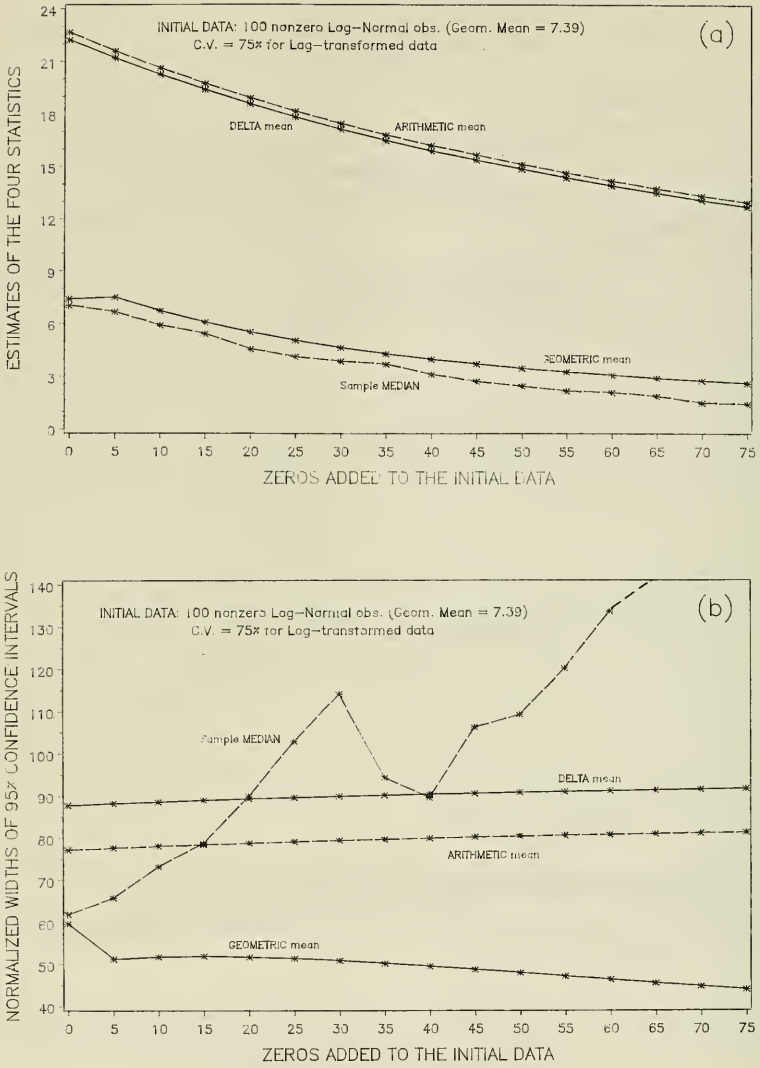
INITIAL DATA: 100 nonzero Log–Normal obs. (Geom. Mean = 7.39)
C.V. = 75% for Log–transformed data
(a)
DELTA mean
ARITHMETIC mean
GEOMETRIC mean
Sample MEDIAN
ESTIMATES OF THE FOUR STATISTICS
ZEROS ADDED TO THE INITIAL DATA
INITIAL DATA: 100 nonzero Log–Normal obs. (Geom. Mean = 7.39)
C.V. = 75% for Log–transformed data
(b)
Sample MEDIAN
DELTA mean
ARITHMETIC mean
GEOMETRIC mean
NORMALIZED WIDTHS OF 95% CONFIDENCE INTERVALS
ZEROS ADDED TO THE INITIAL DATA

Fig. 3 Results of simulating an increasing proportion of zeros in the high-variability data set: a) estimates of the four statistics; b) width of the 95% *CI*'s normalized as a percentage of the estimated statistics.

the 95%*CI* increased noticeably with the data variability, but it was almost unaffected by the proportion of zeros in the data regardless of variability. This is a very desirable property of the δ-*mean* because, in actual applications, the presence of zeros in the data should only affect the estimate of the mean without unduly inflating its standard error. The δ-*mean* was not a good estimator of the middle point of the data. The only correct estimator of central tendency, the median, cannot be recommended for delta-type data because its 95%*CI* was unreliable except for low variability data with less than 30% of zeros (i.e., less than 55 zeros in Fig. 1b). Although for highly variable data the geometric mean tracked the median quite well, its 95%*CI* was also unreliable.

Application to NUEL's Monitoring Data

The δ-*mean* should be the preferred statistic to estimate the population mean when the data contains many zeros (e.g., data from NUEL's programs listed in Table 1). Its usage, however, should be restricted to cases where the nonzero observations are approximately lognormal and the sample size is 15 or larger. A simple approach to testing for lognormality is to log-transform the data and then test for normality using the procedure UNIVARIATE (SAS 1985). The most desirable features of the δ-*mean* mean are an accurate standard error for delta-distributed data and 95%*CI*'s whose relative width (i.e., scaled by the mean) is almost unaffected by the proportion of zeros in the data. The weaknesses of the δ-*mean* are that it does not coincide with the middle point of the data and that, unlike the median, it is not resistant to outliers. The median, however, was shown to have a 95%*CI* which was unreliable except for low variability data with less than 30% of zeros. When the data contain only a few zeros (less than 10%), either the median or the geometric mean should perform reasonably well with low to moderate variability (CV < 50% for log-transformed data).

In actual applications to monitoring data on species that occur seasonally, the cut-off points in the data series must be chosen consistently to insure comparability among years. The following procedure is suggested: 1) for each species, start and end the data series on the dates of the first and last occurrence of that species each year and ignore any zero data collected before and after; and 2) compute the cumulative distribution of the data series (i.e., by adding observations sequentially) and trim the two tails of the distribution by 2.5%, so that only the central observations adding up to 95% of the total sum are retained. It should be noted that this procedure will result in annual data series that will generally vary in length and starting and ending dates from year to year. This poses no problem for estimating correct annual δ-*means* and insures that the data series are a consistent and fair representation of the annual occurrence of each species.

Finally, the lengthy computation of the δ-*mean* and its standard error should be carried out using a computer program. Such a program was written for the simulation study described above and it is available at NU's computer system. The accuracy of this program was tested by reproducing the results of Pennington (1983).

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Hydrothermal Studies

Introduction

During 1987, Northeast Utilities Service Company (NUSCO), on behalf of Northeast Nuclear Energy Company (NNECO), completed a survey of the extent and configuration of the thermal plume generated from the combined output of all three nuclear power plants at the Millstone Nuclear Power Station (MNPS). This survey was completed to meet two needs. The first was to determine whether the NPDES Permit (CT 0003263) condition restricting the plume size had been met. The Permit states that

> *the permitee shall operate all facilities in such a manner as not to raise the average temperature of the receiving waters more than 4°F or increase the normal temperature of the receiving waters above 83°F. For purposes of this condition, cognizance will be given to reasonable time and distance to allow mixing of effluent and receiving waters, but the boundary of the mixing zone shall not exceed a radius of 8,000 feet from the discharge outlet at the quarry cut.*

The second was a commitment made by NUSCO on behalf of NNECO in a letter dated 23 July 1986, to the Connecticut Department of Environmental Protection (CT DEP) (NUSCO 1986). In this letter NUSCO agreed

> *to verify thermal plume predictions and to map the extent of the 3-unit thermal plume during varying tidal conditions, and to undertake additional thermal plume studies in 1987. The objective would be to implement the field studies when all three units were operating simultaneously at or near 100% power.*

The work completed during 1987 included water temperature and dye concentration surveys during the period 21-27 August 1987 to determine the water temperature rise due to the plant discharge and resulted in plots of isotherms of plume configurations during four tidal regimes.

The specific objectives of the field studies were to

1. Provide dye concentration measurements that would distinguish temperature rise in Long Island Sound due to heated circulating water discharge from heating due to solar radiation and other natural sources.

2. Provide information on the effect of three-unit circulating water discharge on the hydrographic and thermal characteristics of the receiving waters off Millstone Point during four tidal phases: max ebb, slack after ebb, max flood and slack after flood

The thermal plume survey was a cooperative effort involving Ocean Surveys, Inc. (OSI), and NUSCO staff. OSI provided instrumentation for positioning, dye delivery, flouromctry and temperature recording and expertise for thermal contour mapping. NUSCO provided necessary boat and staff support. The survey data were supplemented by continuously recorded temperature data collected during October 1987 at strategic locations by NUSCO staff. This document summarizes past hydrographic studies, presents the methodology and results of those done during 1987 and compares the results of these studies to three-unit thermal plume predictions.

Review of past studies

Since 1966, NUSCO has retained several different investigators to perform hydrographic and hydrothermal surveys in the vicinity of Millstone Point (Table 1). Synopses of the results follow.

TABLE 1. Chronology of MNPS hydrographic and hydrothermal studies.

Year	Study
1965	Stone & Webster Engineering Corporation. Thermal effects analysis for a 1,200 MW plant at the Millstone Site. Units 1 and 2 Environmental Report, Docket Nos. 50-245 and 50-336, Appendix B, Section III-A.
1965	Essex Marine Laboratory. Current velocity, temperature and salinity measurement in the Millstone Point area.
1965	U. S. Coast and Geodetic Survey. Study on tidal current data. Units 1 and 2 Environmental Report, Docket Nos. 50-245 and 50-336, Appendix B, Section III-H.
1966	Bechtel Corporation. Diffusion patterns of the circulating water discharge effluent for the Millstone Project. Units 1 and 2 Environmental Report, Docket Nos. 50-245 and 50-336, Appendix B, Section III-B.
1966	Pritchard-Carpenter Consultants. Continuous discharge tracer study, Twotree Island Channel and Niantic Bay, Long Island Sound. Units 1 and 2 Environmental Report, Docket Nos. 50-245 and 50-336, Appendix B, Section III-C.
1968 - 69	Raytheon Corporation. Millstone survey, study on salinity - temperature profiles. Units 1 and 2 Environmental Report, Docket Nos. 50-245 and 50-336, Appendix B, Sections II-D and E.
1970	Pritchard-Carpenter Associates. Tracer study of the circulating water system, Millstone Point Unit 1 and 2 Environmental Report, Docket Nos. 50-245 and 50-336, Appendix B, Section III-F.
1971	VAST, Inc. Unit 1 June 1971 Millstone Point temperature survey. Units 1 and 2 Environmental Report, Docket Nos. 50-245 and 50-336, Appendix B, Section III-G.
1971	VAST, Inc. Dye diffusion survey in Twotree Island Channel Units 1 and 2 Environmental Report, Docket Nos. 50-245 and 50-336, Appendix B, Section III-J.
1972	VAST, Inc. Study of an offshore thermal diffuser outfall by dye simulation. Units 1 and 2 Environmental Report, Docket Nos. 50-245 and 50-336, Appendix B, Section III-K.
1972	VAST, Inc. Unit 1 thermal survey. Units 1 and 2 Environmental Report, Docket Nos. 50-245 and 50-336, Appendix B, Section III-I.
1973 - 74	Braincon Corporation. Hydrographic surveys. August-September 1973 and February 1974.
1977	Environmental Devices Corporation. Postoperational Units 1 and 2, preoperational Unit 3 hydrothermal survey of the Millstone Nuclear Power Station. Millstone Nuclear Power Station, Unit 3, Environmental Report, Operating License State, Appendix D.
1977	Texas Instruments, Inc. Airborne thermal infrared survey, Millstone Point Nuclear Station. Millstone Nuclear Power Station, Unit 3, Environmental Report, Operating License State, Appendix D.

1965 - 1976

An analysis of the thermal effect of a proposed nuclear power plant, with a capacity of 1,200 MWe and a design circulating water flow of 1560 cfs (44.2 m^3/s) and a 20°F (11°C) rise, was made in May 1965 by Stone & Webster Engineering Corporation. It was assumed that the circulating water would be discharged from the southern end of the quarry into Long Island Sound. The purpose of this analysis was to provide a basis for predicting thermal effects that would result from the operation of Millstone Unit 1.

In 1965, Essex Marine Laboratory obtained field data to serve as a basis for the initial calculations of thermal distribution patterns. Their observations established the existence of strong tidal currents in Twotree Island Channel (see Fig. 1 for orientation) and provided information on velocity, temperature, and salinity profiles in the area of the proposed circulating water discharge for Unit 1. These data were supplemented by tidal current measurements made during the same period by the U.S. Coast and Geodetic Survey (now the National Ocean Survey). These measurements were made at the following locations:

Twotree Island Channel, 0.2 mi (0.3 km) south of Bartlett Reef, and Niantic River railroad bridge. Continuous measurements were made for approximately four days. Measurements in Twotree Island Channel and Bartlett Reef consisted of current speed and direction measurements at three different depths.

A study of the diffusion patterns of the circulating water discharge effluent was made by Bechtel Corporation (1966). The objective of this study was to determine the flow and diffusion patterns of the condenser discharge with the aid of a small scale hydraulic model. The hydraulic characteristics of the model were correlated with local field data furnished by the Essex Marine laboratory and the U.S. Coast and Geodetic Survey. The model study used tracers to indicate the general flow patterns of the tidal current in the vicinity of Millstone Point. Although the variations of the water temperature in the effluent were not predicted from this technique, the study provided local flow patterns in the Millstone area.

In May of 1966 Pritchard-Carpenter (1967) conducted Rhodamine B dye tracer tests prior to the operation of Unit 1 to determine the dilution off Millstone Point that resulted from the natural action of tides and wind. To simulate the action of the Unit 1 circulating water system, which was not functional at the time, Rhodamine B dye was released through 1/8-in (3.2-mm) holes in a 5-ft (1.5-m) pipe located 450 ft (137 m) offshore of the proposed discharge point. The results provided estimates of the rates of mixing and dilution of chemical discharges, and cooling of the heated water. However, the thermal predictions did not reflect induced entrainment due to discharge momentum nor did they reflect the effect that stratification would have on the discharge of warm water. Thus, the predictions were considered conservative for design purposes.

During August 1968 and March 1969 Raytheon Marine Research Laboratory (1968, 1969) made temperature and salinity measurements at three points in the greater Millstone bight to obtain vertical temperature and salinity distributions. These points represented the general locations of the ends of the Unit 1 thermal plume during ebb and flood tide as predicted by Pritchard-Carpenter (1967). The purpose of these surveys was to obtain reference information on typical summer and winter temperature-salinity characteristics.

During February 1970 several tests were conducted (Pritchard-Carpenter 1970) with the Unit 1 circulating water system operating at full flow, but at ambient water temperature. A 30-percent Rhodamine B solution was injected into the intake at 10 ml/min. The purpose was to evaluate the combined effect of momentum entrainment resulting from the velocity of the discharge and the natural mixing characteristics produced by tidal currents. Because there was no heat rejected to the cooling water, the effects of stratification were not determined.

In June 1971, VAST, Inc. (1971a) conducted a temperature survey of three-dimensional thermal distribution patterns as they actually occurred during full operation of Unit 1. The study used a surface transect method to reduce the measurement time required for each of four surveys; one during maximum flood, maximum ebb, slack after flood and slack after ebb. These surveys indicated the position of the thermal plume and provided the information necessary for the strategic collection of temperature at depth profiles. The resulting profiles indicated the three-dimensional structure of the thermal plume and, in deeper water, determined the depth of the thermal plume. However, no compensation was made for the onshore warming temperature gradient characteristic of the spring and summer months. Thus, the areas enclosed by contours representing water temperatures of 1.5°F and 4.0°F (0.83°C and 2.2°C) above ambient (ΔT) were overestimated.

In November 1971 and March 1972, VAST, Inc. (1972b) conducted temperature surveys to define and map the thermal plume from Unit 1 independent of thermal inputs from natural sources. Dye was injected at a constant rate into the Unit 1 discharge while the unit was at full load, and all four circulating water pumps and

two service water pumps were in operation. Dye concentrations were measured continuously in the quarry and from boats moving along prescribed transects. The dye concentration and temperature data were digitized at predetermined grid points and converted to the equivalent temperature rise to obtain synoptic patterns of the thermal plume. These results were in closer agreement with predictions than the June 1971 study (NUSCO 1979). The differences between the prediction of May 1966 and those of February 1970 in the near field were attributed to the effects of momentum entrainment which had not been compensated for in the 1966 study.

VAST, Inc. conducted two other dye studies (1971a, 1972c). Each was designed to determine the natural flushing or renewal rate of Long Island Sound water in the vicinity of Millstone Point due to tidal exchange. The surveys were required for use in the conceptual design of a multiport diffuser system that might be located in Twotree Island Channel or west of Twotree Island for cooling water discharge. During both surveys Rhodamine B dye was injected from boats in these two areas and dye concentrations were sampled continuously from boats moving along prescribed transects.

In 1972, Stone and Webster Engineering Corporation (SWEC) completed a modeling effort that resulted in preliminary thermal plume predictions presented in the Environmental Reports for Unit 2 and Unit 3 (MPC 1972a, 1972b).

Hydrographic surveys were conducted in the Niantic Bay area of Long Island Sound during August and September 1973 and February 1974 (Braincon 1975). Tide levels, tidal current speed and direction, and wind speed and direction were measured. These data were analyzed and the tide levels were used as input for the SWEC two-dimensional tidal circulation model; the current data were used to verify this model.

1977 Hydrothermal survey

During 1977, as required by the Nuclear Regulatory Commission, a hydrothermal field survey of the two-unit operational plume from MNPS, was conducted (ENDECo 1978; TI 1978). The objectives of this survey were to determine the three-dimensional temperature characteristics of the thermal plume resulting from the discharge of condenser cooling water from Units 1 and 2 and to verify the original 1972 predictions of the two-unit plume. The details of these studies are best described in contractor reports (ENDECo 1978; TI 1978) but are summarized briefly.

The dye study provided detailed information on dilution rates and three-dimensional temperature distributions (ENDECo 1978). Rhodamine WT dye was introduced into the Units 1 and 2 circulating water discharges during full plant load conditions to achieve 16 ppb at the quarry cut (ENDECo 1978). During a two-day period (one complete tidal cycle each day) dye concentration and temperature were monitored continuously at each intake, the quarry cut and from boats that followed six predetermined transects. It took the boats about one hour to complete all six transects; boat position was determined from four transponders. In the near field (an area defined as 500 ft (152 m) from the center line of the discharge plume out to 1000 ft (305 m)), dye concentration and temperature were measured vertically (5-ft (1.5-m) at intervals down to 30 ft (9 m)) and horizontally 1.5 ft (0.5 m) below the surface. These data were used to map the plume over a complete tidal cycle. Temperature isotherms and dye concentration isopleths were drawn manually on a map.

Thermal infrared scanning provided a synoptic 'picture' of the surface thermal plume at specific tidal stages. The 8- to 14-micrometer portion of the electromagnetic spectrum was scanned coincident with the dye study (TI 1978). Temperature reference sources within the field-of-view provided ground truth calibration. The recorded airborne thermal infrared data were presented both qualitatively and quantitatively.

Comparisons of the temperature and dye plumes and the infrared survey indicated that the shape and extent of the temperature and dye plumes for some tidal phases were in general agreement with each other (NUSCO 1979) (Tables 2 and 3). When compared to two-unit predictions, however, it was clear that the distance to the 1.5°F (0.83°C) isotherm exceeded predictions for the max ebb tide stage.

TABLE 2. Comparison of predicted and actual surface areas encompased by selected ΔT isotherms produced during two-unit operation.

Tide stage	Area in acres encompassed by each isotherm 8.0°F (4.4°C)	6.0°F (3.3°C)	4.0°F (2.2°C)	1.5°F (0.8°C)
Max Flood				
Predicted for 2 units[1]			47.1	172.0
Hydrothermal survey, 7/29/77[1]	0.8	1.0	7.1	91.1[2]
Infrared survey, 7/29/77[1]	6.4	12.4	140.0	666.0[2]
Slack after flood (high slack)				
Predicted for 2 units			48.2	223.0
Hydrothermal survey, 7/29/77	1.8	7.8	32.5	58.1
Infrared survey, 7/29/77	2.6	12.1	34.5	50.6
Max Ebb				
Predicted for 2 units			33.1	159.0
Hydrothermal survey, 7/29/77	7.1	10.6	27.3	147.0[2]
Infrared survey, 7/29/77	10.1	65.1	171.0	290.0
Slack after ebb (low slack)				
Predicted for 2 units			56.0	273.0
Hydrothermal survey, 7/29/77	9.0	66.1	186.0[2]	331.0[2]
Infrared survey, 7/29/77	11.6	78.5	243.0[2]	410.0[2]

1 from NUSCO 1979
2 plume areas are limited due to lack of data

TABLE 3. Comparison of maximum predicted and actual distances to selected ΔT isotherms produced during two-unit operation.

Tide stage	Distances in feet from quarry cut to each isotherm 8.0°F (4.4°C)	6.0°F (3.3°C)	4.0°F (2.2°C)	1.5°F (0.8°C)
Max Flood				
Predicted for 2 units[1]			2,300	4,800
Hydrothermal survey, 7/29/77[1]	205	230	1,730	4,000
SWEC predicted, 3 units (extreme)		1,900	2,286	9,700[1]
Slack after flood (high slack)				
Predicted for 2 units			2,200	5,000
Hydrothermal survey, 7/29/77	520	900	1,500	2,200
SWEC predicted, 3 units (extreme)		2,300	3,143	4,000
Max Ebb				
Predicted for 2 units			2,500	4,900
Hydrothermal survey, 7/29/77	780	1,120	1,500	5,500
SWEC predicted, 3 units (extreme)	2,100	3,900	7,428	10,900
Slack after ebb (low slack)				
Predicted for 2 units			2,500	5,400
Hydrothermal survey, 7/29/77	1,150	2,300	3,600[2]	4,800[2]
SWEC predicted, 3 units (extreme)	1,800	4,800	5,428	11,500
S&A predicted 3 units		5,000	8,000	12,000

1 from NUSCO 1979
2 distance estimated from infrared survey on 7/29/77

1978 - present

The results of the 1977 survey indicated that the two-unit thermal plume approached, and exceeded, the 4000-ft limit specified by the NPDES Permit for Units 1 and 2, for short periods as the tide turned during the slack after ebb tidal phase (Stoltzenbach and Adams 1979). Because of these findings and recognizing that the original plume predictions were based on non-transient models, it became apparent to NUSCO that improved modeling was necessary.

During 1978 and 1979, Liang and Tsai (1979) analyzed the data and calibrated an updated mathematical model to predict the thermal plume resulting from the combined discharge of condenser cooling water from all three units. Also, Stoltzenbach and Adams (1979) developed a near field - intermediate field model and coupled it to the existing transient far field model. This model replicated the essential surface and subsurface features of the MNPS thermal plume as observed during two-unit operation and provided reliable estimates of the surface and subsurface induced temperature rise distribution down to a ΔT of 1.5°F (0.83°C). Conservative estimates of the maximum extent (in terms of distance from the discharge point) of 6°F (3.3°C), 4°F (2.2°C) and 1.5°F (0.83°C) induced temperature increases were 5,000 ft (1,524 m), 8,000 ft (2,438 m) and 12,000 (3,658 m) respectively (Stoltzenbach and Adams 1979). The NPDES Permit now limits the 4°F (2.2°C) temperature rise to 8,000 ft (2,438 m).

Several factors were considered when selecting the methodology and dates for the actual plume mapping in 1987. After discussions with advisors (J. Tietjen, N. Marshall, S. Saila, W. Pearcy) and regulators, NUSCO determined that the configuration of the thermal plume during late summer, when ambient water temperatures were near maximum, would represent worst case conditions. Mapping would have to include a dye survey so that natural daily warming could be separated from the heat load added by the Station. Also because NUSCO wanted to determine the maximum extent of the three-unit thermal plume, the survey would have to be completed when all MNPS units were operating at near-maximum capacity. Because of scheduled refuel outages (Unit 1, July and August 1987 and Unit 3 to begin 31 October 1987), a window of appropriate conditions would occur in 1987 only during late August. After that, water temperature would have cooled considerably from its normal summer maximum.

Materials and Methods

As mentioned previously, Ocean Surveys, Inc. (OSI), Old Saybrook, Connecticut, provided instrumentation and technical support to complete the actual dye survey. Preliminary activities began 21 August 1987 and data collection began 23 August 1987. Actual mapping of the thermal plume during four major tidal phases (low slack, max flood, high slack and max ebb) took place on 26 August 1987. The survey data were supplemented with continuous in-situ temperature records taken subsequent to the actual plume mapping. Details of instrumentation and data aquisition techniques used during the mapping survey are described in the OSI report, which is the Attachment to this section. A brief summary is given below along with a description of methodology used by NUSCO to collect in situ supplemental temperature during October 1987.

Dye injection

Dye plume mapping was accomplished using Rhodamine WT flourescent tracer dye. Dye was injected onto the water surface immediately downstream of the Unit 3 discharge. Mixing occurred here and where the waters from Units 1, 2 and 3 met in the middle of the quarry. Dye concentration and water temperature were monitored continuously at one quarry cut using a calibrated Turner Model 111 flourometer and a Yellow Springs Instrument Company Series 700 thermistor, respectively. To insure that the dye injection rate remained constant, NUSCO staff checked the flow of dye, weighed the dye supply reservoir and checked the flourometer every two hours. Background levels of flourescence were

recorded from 1700 hours, 21 August to 1400 hours, 22 August. Dye injection began at 1500 hours on 23 August 1987, at a rate of 5 lb/h (1.85 kg/h). This was increased to 7 lb/h (2.6 kg/h) 26 hours later so that a dye concentration of 2.2 ppb by weight was achieved at the quarry cut. Dye concentrations at the cut were first observed about 3 hours after dye injection began and stabilized there about 10 hours after changes occurred at the injection point. Dye injection was suspended at 1750 hours on 26 August at the conclusion of the intensive mapping period (0657 to 1605 hours, 26 August 1987); flourescence at the quarry cut continued to be monitored until 1200 hours on 27 August 1987.

Survey vessels

Two NUSCO vessels, 'Northeast I' and 'Northeast II', were equipped with instrumentation appropriate for use during the intensive mapping phase of the study. Both vessels had Turner Model 10 flourometers equipped with thermistors. 'Northeast I' was rigged to allow surficial dye concentration and temperature measurements to be taken along 41 predetermined transects during the four tidal mapping sessions. The transects were oriented nominally perpendicular to the axis of the thermal plume and along well defined plume boundaries. 'Northeast II' was rigged to collect depth profiles of temperature and dye concentration at 27 specific locations to characterize the vertical mixing of the thermal plume.

Survey vessels were positioned using either a computerized system, developed by OSI, that permits an accuracy of ± 50 ft (15 m) or a manual system employing a hand-held VHF range finder. Where the computerized system could be used, the person at the helm could locate the vessels' position with respect to the intended survey trackline on a video monitor. The desired trackline could be followed by making course corrections indicated on the display. Where site conditions did not permit the use of the computerized system, the survey vessel was controlled along a bore sight representing the intended survey transect by the transit operator using the VHF range finder. In all cases, actual position data were automatically recorded; tracklines are presented in the Appendix to this section.

In situ current, temperature and salinity monitoring

Continuous measurements of current speed and direction, and water temperature and salinity, were obtained from an Endeco Type 174 in situ recording device positioned at stations east and southeast of Millstone Point (Attachment Fig. 1). Stations JCE and JCW were occupied on 24 and 25 August and TTIC and MP were occupied on the day of mapping, 26 August.

Between 8 and 29 October 1987, NUSCO staff deployed two solid-state temperature recorders (TempMentors), which continuously logged water temperatures at two depths, at seven stations (Fig. 1). These data loggers provided additional information on the variability of the position and extent of the thermal plume between tidal stages and under a variety of meterological and operational conditions. The date and duration of each deployment are listed in Table 4. The loggers were returned to the lab and data was processed using an IBM PC.

TABLE 4. Deployments of the TempMentor continuously recording thermistors during 1987. At each location a thermistor was set 1 m below the surface and 1 m above the bottom.

Date	Location*	Duration
10/8/87	1	108 h
10/13/87	2	75 h
10/16/87	3	76 h
10/21/87	4	48 h
10/23/87	5	51 h
10/26/87	6	51 h
10/29/87	7	96 h

* see Fig. 1

Presentation of isothermal data

Because both dye concentration and water temperature are considered conservative, the percent drop in the temperature of the plume with respect to the total temperature difference between the discharge water and the receiving body of water

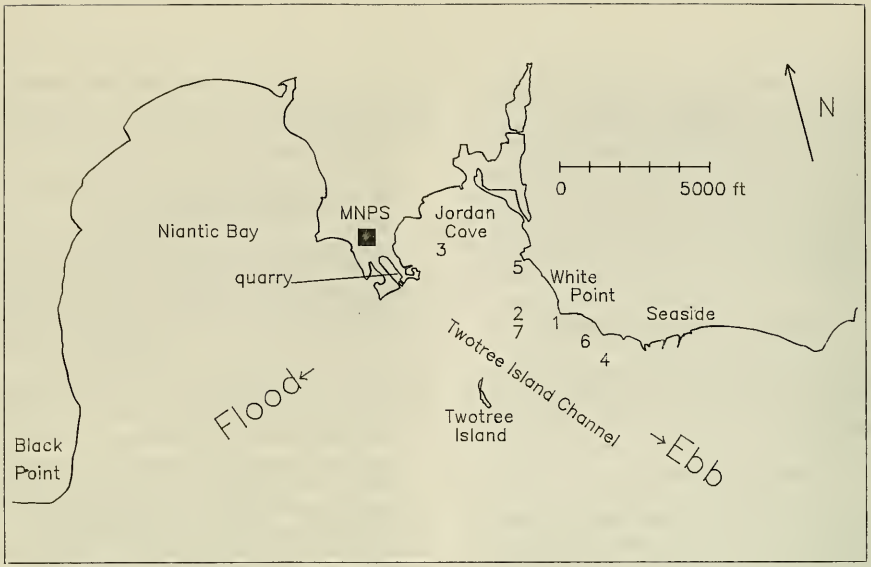


Fig. 1. The location of MNPS. TempMentor deployment locations are designated by the numerals "1" through "7".

is equal to the percent dilution of the dye in the plume with respect to the dye concentration of the discharge water at the quarry cut. Dye concentrations (ppb by weight) were converted to degrees Farenheit above ambient temperature (ΔT) and plotted on a trackline map for each of the four surveys. Because heat loss to the atmosphere was neglected, the indicated temperature increases were higher than actual, particularly in the far field. These data were contoured at the 1.5, 4, 6 and 8°F (0.83, 2.2, 3.3 and 4.4°C) ΔT levels. Data from the vertical profiles were also developed; these were plotted as ΔT versus depth.

Results

The results of 1987 hydrothermal studies completed between 20 August and 15 November 1987 follow. The results include those from both the OSI-supported dye study and the NUSCO-deployed temperature data loggers.

Environmental conditions

Meterological conditions in the vicinity of MNPS during August through October reflect the seasonal transition from summer to autumn. Based on historical data acquired during eleven years from the environmental data aquisition network (EDAN), air temperature decreases from an average of about 22°C in early August to about 10°C by the end of October (Fig. 2). Water temperatures decrease from an average of 20°C in early August to 14°C in late October (Fig. 2). Winds tend to be light (2 - 2 m/s) in early August, and increase in intensity to 3 - 6 m/s in October (Fig. 2). Winds tend to be out of the north in August, and from the west northwest in October (Fig. 3). Although, conditions during this period in 1987 were fairly typical of historical conditions (Figs. 2, 3), a storm occurred 21-22 August 1987, three days before the dye mapping. Wind speed varied between 2 and 7 m/s during the period the

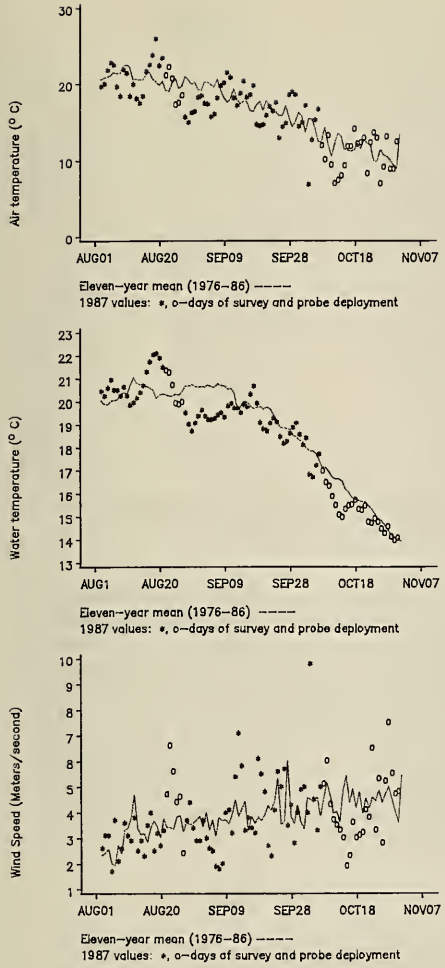


Fig. 2. Air and water temperature, and wind speed recorded by the environmental data acquistion network (EDAN), August through October, 1976 - 1986. Ambient water temperatures (°C) are averages of those measured at 15-minute intervals at the MNPS Units 1 and 2 intakes. Air temperature and wind speed are averages of measurments taken at 15-minute intervals, 10 m high on the meterological tower.

TempMentors were deployed and water tempertures were below the 11-year mean.

Dye concentration mapping was conducted under nearly ideal weather conditions (26 August). Seas were calm (less than 0.3 m), reducing thermal plume mixing due to wave action to a minimum. The light winds, averaging 2 m/s (Figs. 2, 3), assured that the dispersal of the thermal plume was due predominantly to tidal influences. Conditions were good enough to allow surface expression of the plume boundaries during maximum flood, high slack and maximum ebb stages of the tide. A further benefit of the good conditions was the development of the 1.5°F (0.83°C) isotherm. Greater wind and wave action would have diminished the lateral extent of this isotherm. Thus, error-free equipment operation combined with excellent site conditions allowed for the clear definition of this isotherm.

Station operating conditions

All three MNPS units normally operate at a constant base load. Unit 1 resumed power production on 19 August 1987 subsequent to the completion of its refuel outage. Power production reached 100 % capacity on 21 August 1988 (Fig. 4). During the background monitoring period, the dye build-up period, and low slack and max flood mapping periods (0900 on 26 August 1987) all three units operated at full capacity and pumped a total of 4,364 cfs (124 m^3/s) of cooling water (Fig. 4). Between 0900 and 1400 hours on 26 August, Unit 1 power production was reduced. Concurrently, Unit 1 cooling water usage was reduced from 989 cfs (28 m^3/s) to 521 cfs (15 m^3/s) and the effluent water temperature dropped about 1°C (Fig. 5). The Station, however, was still using 94% of its maximum cooling water at 1200 hours, during the high slack mapping session, and nearly 90% of its maximum at 1430 hours, the start of the maximum ebb tide mapping session. Considering the nearly ideal survey conditions, these reductions in discharge volume should not have greatly altered the patterns and magnitudes of the plume from those presented; adverse wind and sea conditions could be expected to

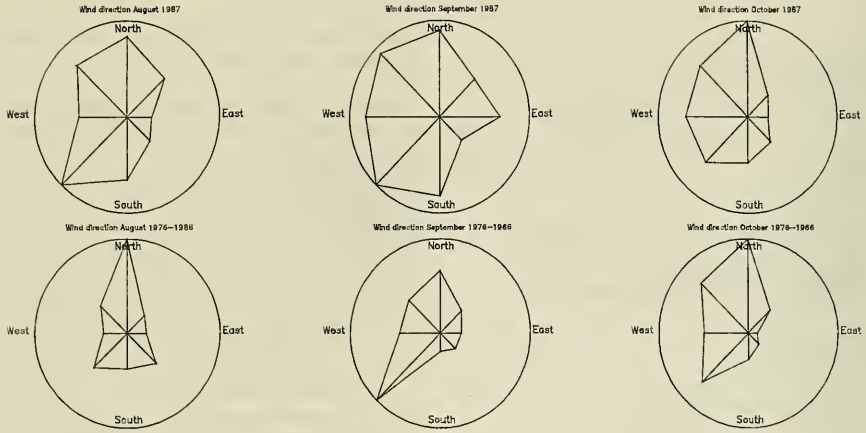


Fig. 3. Frequency of 15-min observations of wind direction as measured at the 30-m level on the meterological tower, August through October.

have a much greater impact on the thermal plume.

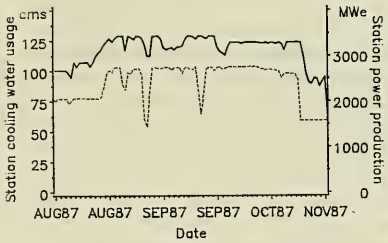


Fig. 4. Station cooling water usage (—, million m^3/second) and power production (---, MWe) August through October 1987.

Temperature and dye plume mapping

As expected the the MNPS 3-unit thermal plume moved and shifted in the direction of the prevailing currents (Attachment Figs. 10 - 13). Under the survey conditions on 26 August 1987, the discharge water cooled to 4°F (2.2°C) above ambient within 3,750 ft (1,143 m) of the quarry cut on all tidal stages. At low slack, the plume pooled in an area from southwest to east of Millstone Point and extended toward Twotree Island. During maximum flood the plume was swept by the tide along Millstone Point, westward into Niantic Bay. At high slack the plume again pooled in an area southeast of Millstone Point but did not extend as far as Twotree Island. During maximum ebb the plume extended into and followed Twotree Island Channel.

Low slack

During the low slack survey (0657 - 0811 hours), the plume was fairly well distributed about the quarry cuts. The 4°F (2.2°C) isotherm extended out to 3,500 ft (1,067 m) off the cuts; it also extented at the north into the eastern part of Jordan Cove to 3,760 ft (1,146 m, Attachment Fig. 10). The 6 and 8°F (3.3 and 4.4°C) isotherms defined the edges of the discharge jet. The 4°F (2.2°C) isotherm extended to the bottom out to 500 ft (152 m) from the quarry cuts (LS1 and

Fig. 5. Effluent and intake water temperatures (°C), total station cooling water flow (cfs), and wind speed (m/s) and direction, taken at 15-minute intervals on the day of dye mapping (26 August 1987).

Attachment Fig. 14). At 2,000 ft (610 m) from the cuts, the base of the plume (as indicated by the 1.5°F (0.83°C) isotherm) was 10 to 15 ft (3 to 5 m) below the surface (LS3 on Attachment Fig. 14).

Maximum flood

During the maximum flood (0848 - 1019 hours), strong currents carried the thermal plume to the west (Attachment Fig. 11). Mixing diluted the plume so that the 4°F (2.2°C) isotherm extended a maximum of 2,000 ft (610 m) to the west in a narrow tongue; the 1.5°F (0.83°C) isotherm was observed much farther west where it appeared to begin separating into multiple branches. A well defined edge to the plume was defined by a change in surface water texture and a line of foam on the surface; dye concentration readings dropped to background levels as this line was crossed. The 4°F (2.2°C) isotherm extended to the bottom in the vicinity of the cuts, but was confined to the upper 10 ft (3 m) 1,000 ft (305 m) southwest of the cut (MF1 and 3 on Attachment Fig. 15). The 1.5°F (0.83°C) isotherm was less than 5 ft (1.5 m) from the surface 4,000 ft (1,220 m) west southwest of the cuts (MF5 on Attachment Fig. 15).

High slack

During the high slack survey (1213 - 1308 hours), the thermal plume was rather evenly distributed about the cuts and the center was shorter and broader than during previous tidal phases (Attachment Fig. 12). This difference was probably due to the difference in tide elevations. During low slack the water elevation between the cut and Long Island Sound is greatest, producing higher discharge currents there than during high slack; the greater currents would tend to carry the plume jet further offshore. The 4°F (2.2°C) isotherm extended 2,100 ft (640 m) offshore while the 1.5°F (0.83°C) isotherm was approximately 3,000 ft (914 m) off the cuts. About 125 ft (38 m) offshore (HS1 on Attachment Fig. 16), the base of the plume was 20 ft (6 m) deep and was within the top 10 ft (3 m) beyond 1,000 ft (305 m) from the cuts.

Maximum ebb

During the maximum ebb survey (1434 - 1605 hours), the thermal plume was carried eastward into Twotree Island Channel (Attachment Fig. 13). The 4°F (2.2°C) isotherm extended out 2,500 ft (762 m) to the southeast and 3,300 ft (1,006 m) to the northeast into Jordan Cove. The 6°F (3.3°C) isotherm closely followed the 4°F (2.2°C) isotherm. The 1.5°F (0.83°C) isotherm was mapped as a narrow finger extending 12,500 ft (3,810 m) toward the southeast through Twotree Island Channel. In Jordan Cove, the 4 and 1.5 °F (2.2 and 0.83°C) isotherms were limited to the eastern part; no dye was detected in the northern or western parts. The plume (4°F (2.2°C) isotherm) extended down 17, 13, and 4 ft (5, 4 and 1.2 m) at 125, 500 and 1,000 ft (38, 152 and 305 m), respectively, from the cuts (ME1, 2 and 3 on Attachment Fig. 17). As mentioned earlier, Unit 1 reduced power, heat load and circulating water volume usage during the morning of 26 August. Because the Station was still operating at nearly 90% of full capacity, the survey was completed after steady state had been reached and due to the ideal conditions, the distributions of these isotherms are believed to be representative of conditions during maximum ebb.

Supplemental temperature data collection

The TempMentor data loggers were deployed at a range of distances from the quarry cuts during 8 October through 2 November 1987. Deployment #3 was closest, about 1,500 ft (457 m) north east of the cuts; deployment #4 was fartherst, about 7,500 ft (2,287 m) south east of the cuts. Deployments #5, #2, #7, #1 and #6 were set at intermediate and increasing distances from the cuts (see Fig. 1).

The temperatures recorded continuously during the seven deployments provided location-specific water temperature histories (Fig. 6), which reflected both Station operation and environmental conditions (Fig. 7). During deployment #3,

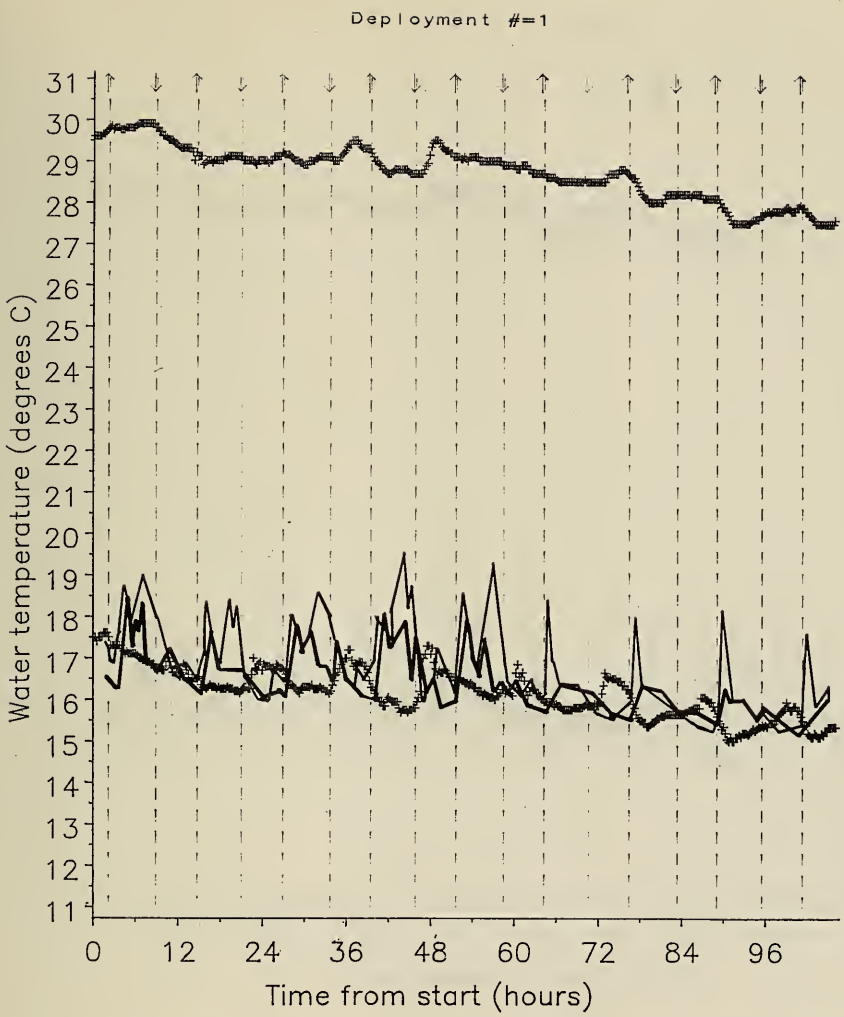
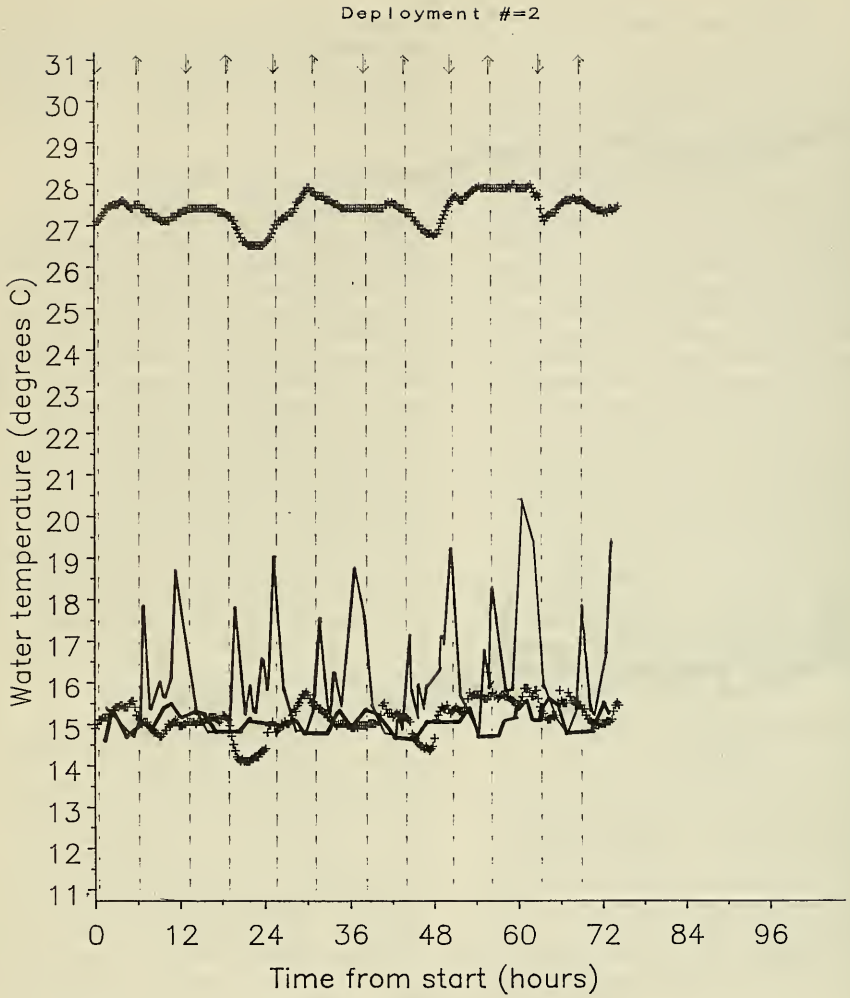


Fig. 6. Surface (—) and bottom (——) water temperatures recorded from TempMentor deployments. The upper and lower lines (+ +) are the effluent and intake water temperatures respectively; times of high (↑) and low (↓) slack are also indicated.



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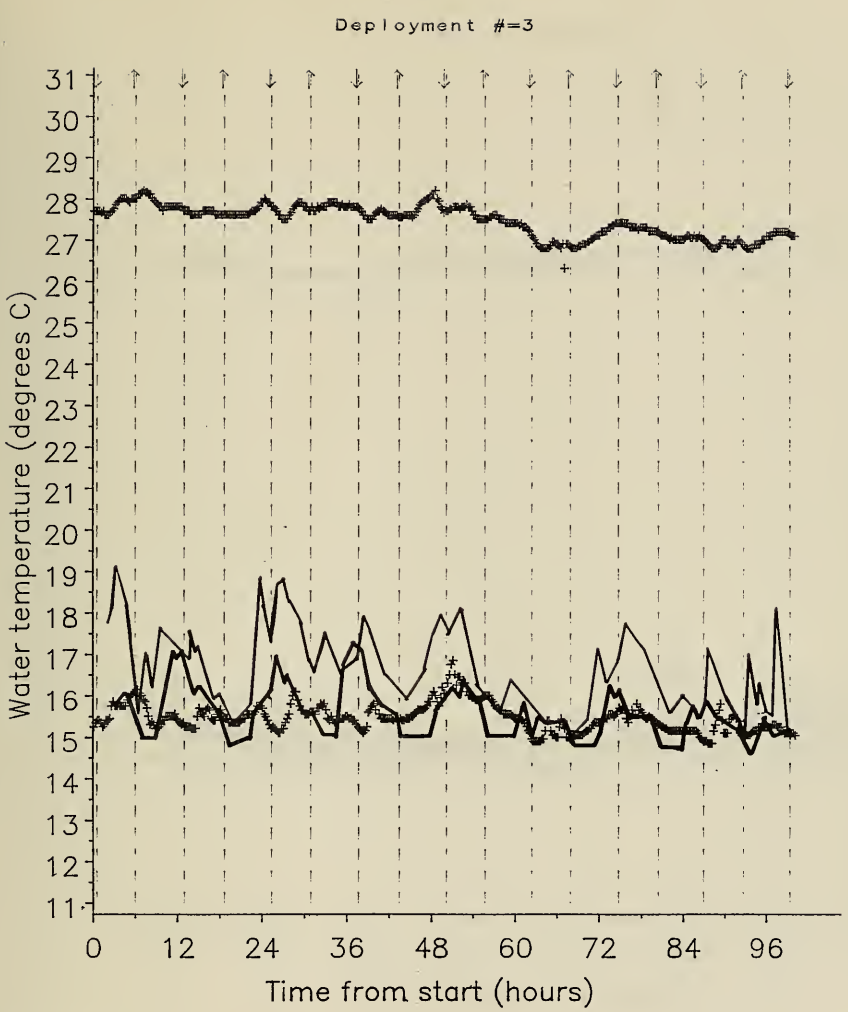

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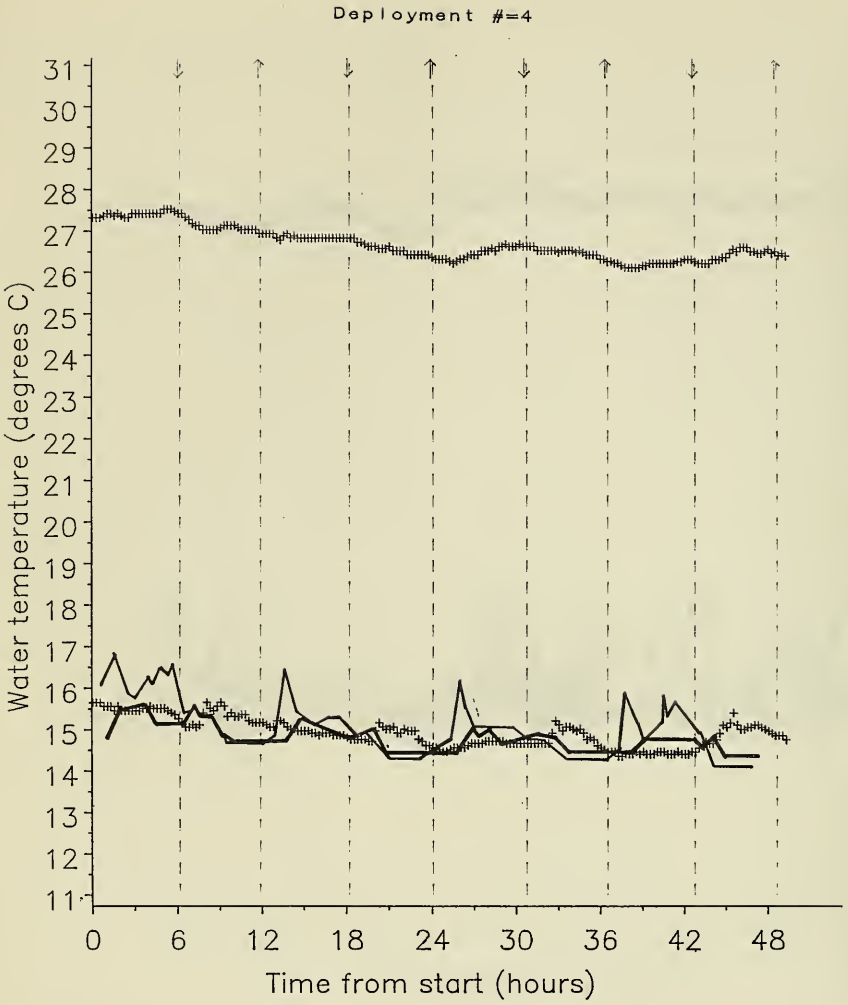

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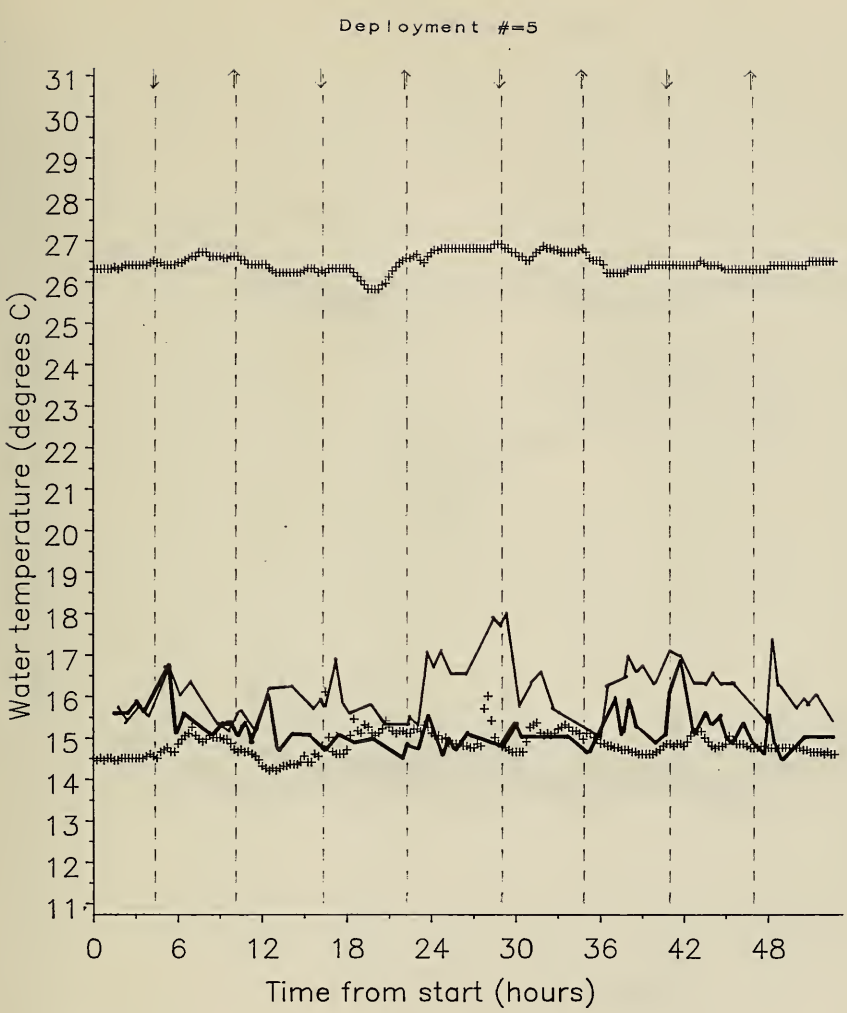

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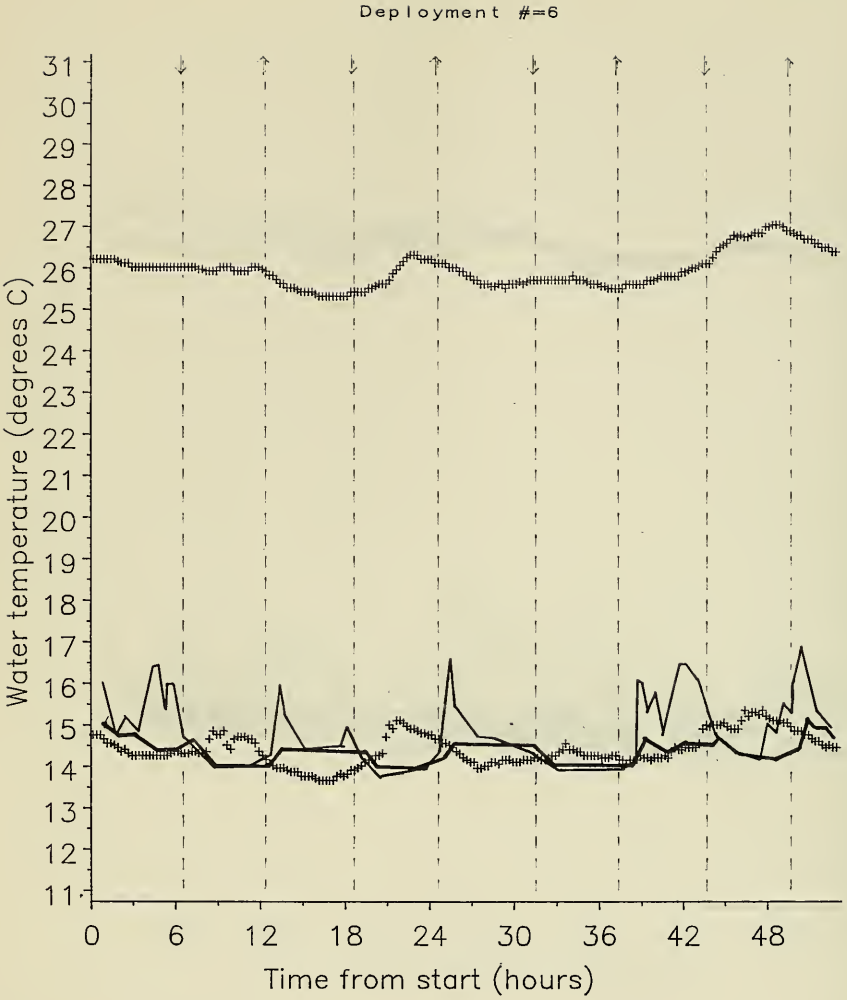

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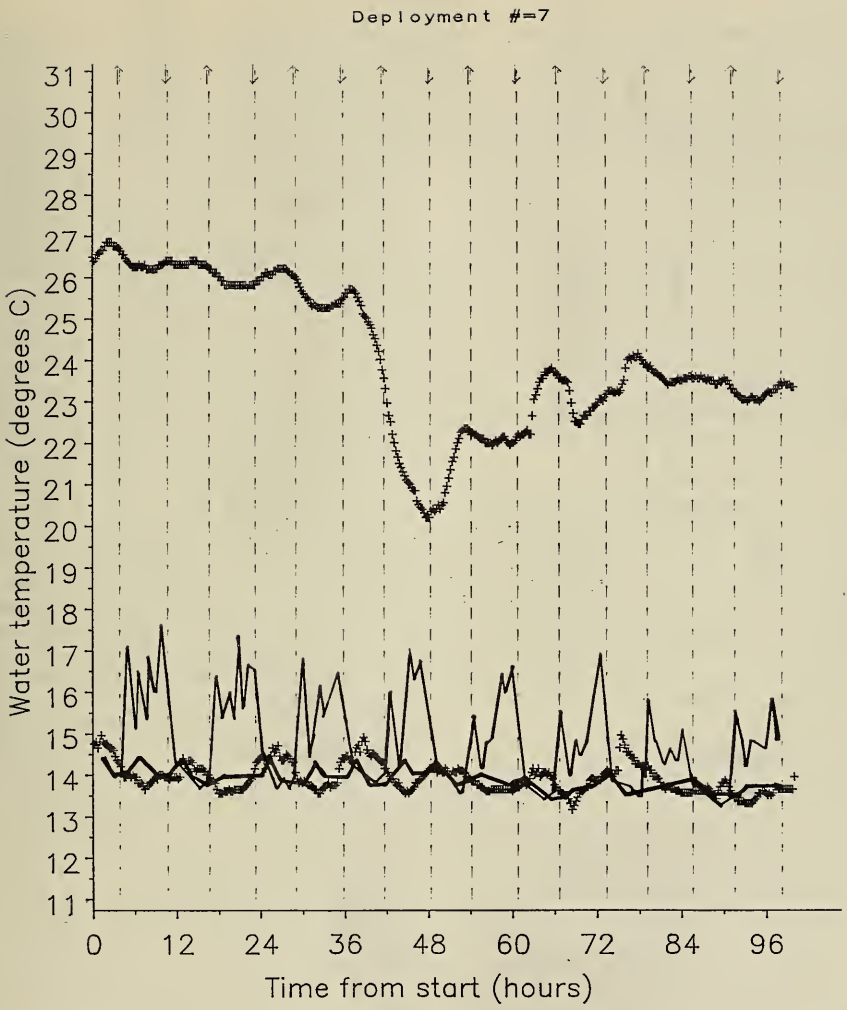

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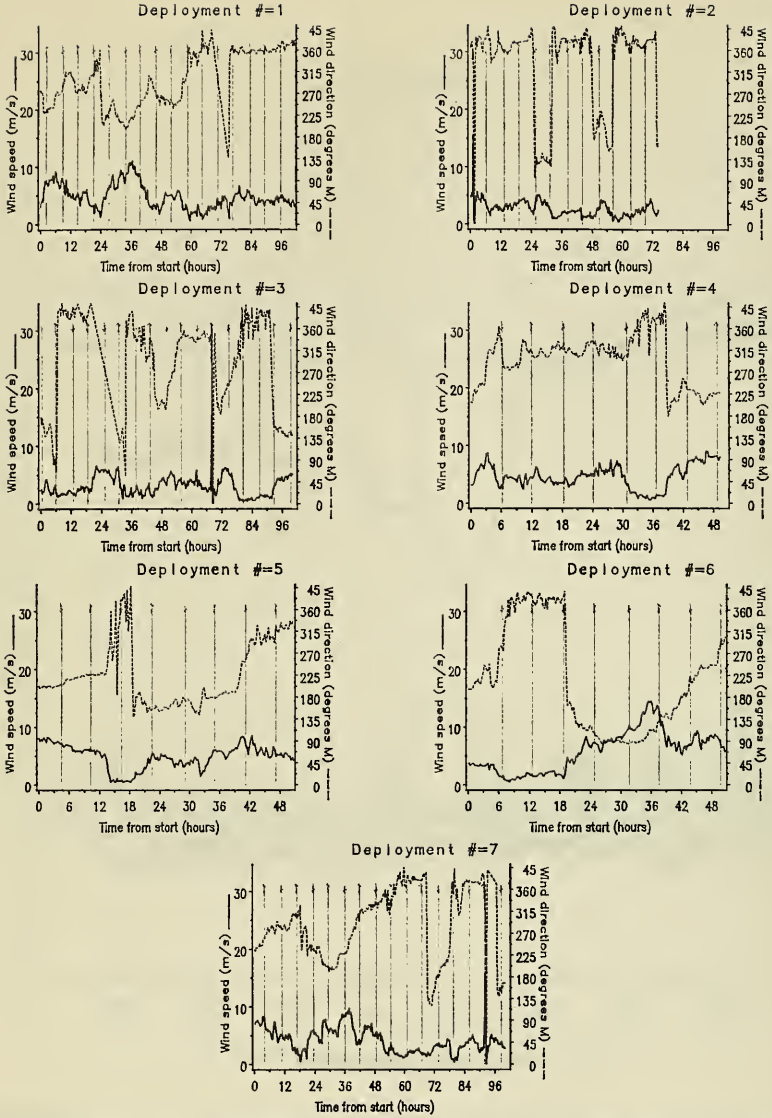

Fig. 7. Hourly observations of wind speed and direction during periods the TempMentor devices were recording water temperatures (8 October through 3 November 1987). Also indicated are times of high (↑) and low (↓) slack.

the plume, as defined by at least a 4°F (2.2°C) temperature rise in water temperature, encountered both the surface and bottom thermistors (Fig. 6), usually at the time of max ebb and low slack. Deviations from this general pattern (e.g. the period 54-66 hours from start) were probably the result of a shift in wind direction (Fig. 7), however neither the surface nor bottom thermistor recorded temperature increases larger than 6°F (3.3°C). At the other extreme, during deployment #4, the data loggers experienced no temperature increases of 4°F (2.2°C) (Fig. 6), although they did record 1.5°F excursions. Surface water temperatures recorded during deployment #6 increased almost 4°F (2.2°C) just after the time of high slack, presumably just as the tide turned, and again just before low slack, if the winds were southerly (Fig. 7). Both surface and bottom thermistors experienced increased water temperatures just after the time of high slack during deployment #1. Also during this deployment, surface water temperature excursions were usually 4°F (2.2°C) or greater; bottom water temperatures usually increased less than 4°F (2.2°C). The temperature records from deployments #2 and #7 were nearly identical. During both of these deployments, only the surface probe experienced brief temperature increases of 4°F (2.2°C) or greater. These excursions were typically bimodal. The first increase occurred at or just after the time of high slack and may have represented warmer water from Jordan Cove passing the probe. The second peak occurred just before low slack, presumbably at or just after the time of maximum ebb and probably represented the MNPS effluent. During deployment #5, warmer water encountered the data logger for longer periods of time than when they were set at locations farther away; temperature excursions rarely exceeded 4°F (2.2°C). During all deployments, slight descrepancies from the general patterns just described were, very likely, the result of shifting wind patterns (see Fig. 7).

Comparison of results to predictions

The configuration and extent of the thermal plume as measured by dye concentrations during each tidal stage surveyed on 26 August 1987 were similar to those predicted (Fig. 8). In general, the area encompassed by the 4°F (2.2°C) isotherm was within 10 acres of the predicted area determined from average conditions and was always less than the area predicted under extreme conditions (Table 5). Further, the distances to the 4°F (2.2°C) isotherm also tended to be similar to the average three-unit predictions and less than the extreme predictions (Table 6). Because the thermal plume predictions were meant to be conservative and because the conditions during the survey were ideal, the measured plume should have been smaller than predicted.

The measured and predicted plumes were most discrepant during the low slack survey (Fig. 8, Tables 5, 6). The actual start of this survey was about 15 minutes after the time of low slack rather than about an hour before low slack as was intended (Fig. 5). Thus the plume portrayed as 'low slack' was probably influenced by increasing flooding currents. However, as indicated previously, the low slack configuration was still within the areas and distances predicted.

The data from the seven temperature probe deployments also supported the conclusion that, although the actual three-unit plume is highly dynamic, it generally conformed to the predicted configuration. For example, temperature records from deployments #5 and #3 indicated the absence of the plume during high slack, which was the predicted situation. Temperatures recorded during deployments #1, #2, #4, #6 and #7 indicated that the plume (4°F above ambient), reached White Point for short periods of time during max ebb and low slack. Again, this situation was predicted, although it was not observed during the dye survey.

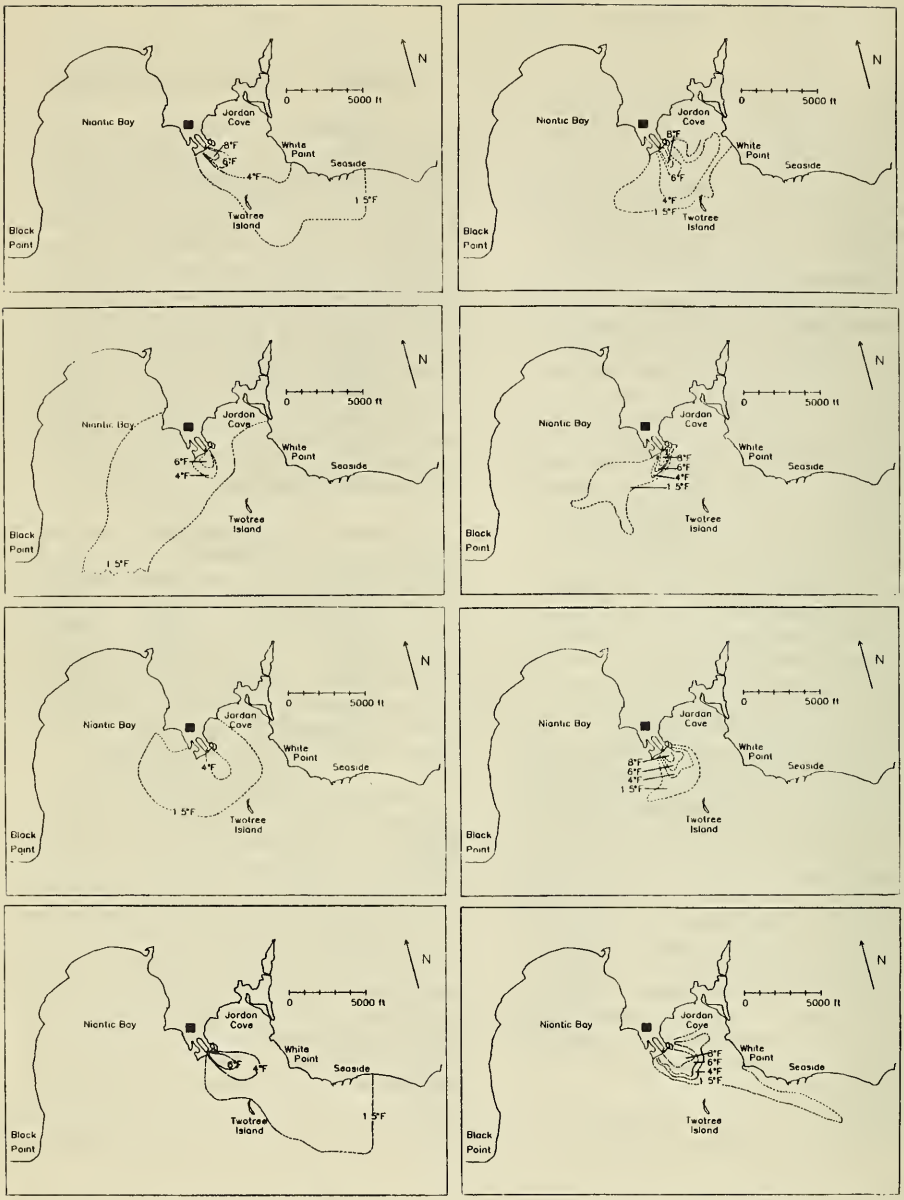

Fig. 8. Locations of selected three-unit thermal plume isotherms. The left column contains predicted locations; the right column contains the locations determined from the 26 August dye survey. The rows, from top to bottom, contain isotherms at low slack, maximum flood, high slack and maximum ebb.

TABLE 5. Comparison of predicted and actual surface areas encompased by selected ΔT isotherms produced during three-unit operation.

Tide stage	Area in acres encompassed by each isotherm 8.0°F (4.4°C)	6.0°F (3.3°C)	4.0°F (2.2°C)	1.5°F (0.8°C)
Low slack				
Predicted for 3 units[1]	6.8	40.8	248.1[3]	1,049.8[3]
Predicted for 3 units (extreme)[2]			583.0	
Hydrothermal survey, 8/26/87	11.5	31.9	241.0	572.8
Max Flood				
Predicted for 3 units		15.3	39.1	1,252.2[3]
Predicted for 3 units (extreme)			59.0	
Hydrothermal survey, 8/26/87	6.9	15.4	26.4	252.1
High slack				
Predicted for 3 units			49.3	353.9
Predicted for 3 units (extreme)			166.0	
Hydrothermal survey, 8/26/8	10.6	32.8	59.0	152.2
Max Ebb				
Predicted for 3 units		23.8	93.6	1,046.4[3]
Predicted for 3 units (extreme)			535.0	
Hydrothermal survey, 8/26/87	27.5	62.9	102.2	443.1

1 determined from average conditions, NUSCO 1983
2 reported in NUSCO 1983
3 limit reached

TABLE 6. Comparison of maximum predicted and actual distances to selected ΔT isotherms produced during three-unit operation.

Tide stage	Distances in feet from quarry cut to each isotherm 8.0°F (4.4°C)	6.0°F (3.3°C)	4.0°F (2.2°C)	1.5°F (0.8°C)
Low slack				
Predicted for 3 units[1]	1,078	1,963	5,968[3]	10,973[3]
Predicted for 3 units (extreme)[2]			5,428	
Hydrothermal survey, 8/26/87	1,580	2,275	3,760	4,800
Max Flood				
Predicted for 3 units		1,155	1,925	8,278
Predicted for 3 units (extreme)			2,286	
Hydrothermal survey, 8/26/87	1,150	1,550	2,000	6,800
High slack				
Predicted for 3 units			2,233	4,620
Predicted for 3 units (extreme)			3,143	
Hydrothermal survey, 8/26/87	,975	1,540	2,160	3,250
Max Ebb				
Predicted for 3 units		1,887	3,465	12,204[3]
Predicted for 3 units (extreme)			7,428	
Hydrothermal survey, 8/26/87	1,980	2,420	3,300[4]	12,500

1 determined from average conditions, NUSCO 1983
2 reported in NUSCO 1983
3 limit reached
4 4°F isotherm extends to 6,000 ft as determined from temperature recorded during deployment #6

A feature of the plume that was apparent from the continuous temperature records, but was not readily apparent from either the dye survey results or the plume predictions was the highly dynamic nature of the plume. Even though the plume reached White Point, it influenced water temperatures there for brief periods only and elevated temperatures did not appear to be sustained there. Further, based on both the survey and supplemental temperature data collected thus far, water temperatures greater than 4°F above ambient do not appear at distances greater than 6,000 ft (1829

m) from the cuts. Even in Jordan Cove, the area most likely to be affected by the thermal effluent, there were respites from elevated temperatures. As temperature records are obtained from thermistors deployed at strategic times and places, our understanding of the highly dynamic thermal plume will be enhanced.

Summary

1. The configuration and extent of the thermal plume produced during three-unit operation, as measured by dye concentration, generally matched predictions during all four tidal regimes.

2. Based on dye concentrations at Unit 1, very little recirculation of discharge water occurs.

3. Water temperatures recorded continuously at selected locations were also generally what was expected, based on predictions.

4. The plume is highly dynamic and those regions influenced by increased water tempeatures generally experienced a respite from warm water for at least several hours during a tidal cycle.

5. Based on both the survey and supplemental temperature data, at no time during the period studied did the 4°F (2.2°C) isotherm appear to extend past the 8,000-ft (2439 m) limit imposed by the NPDES permit.

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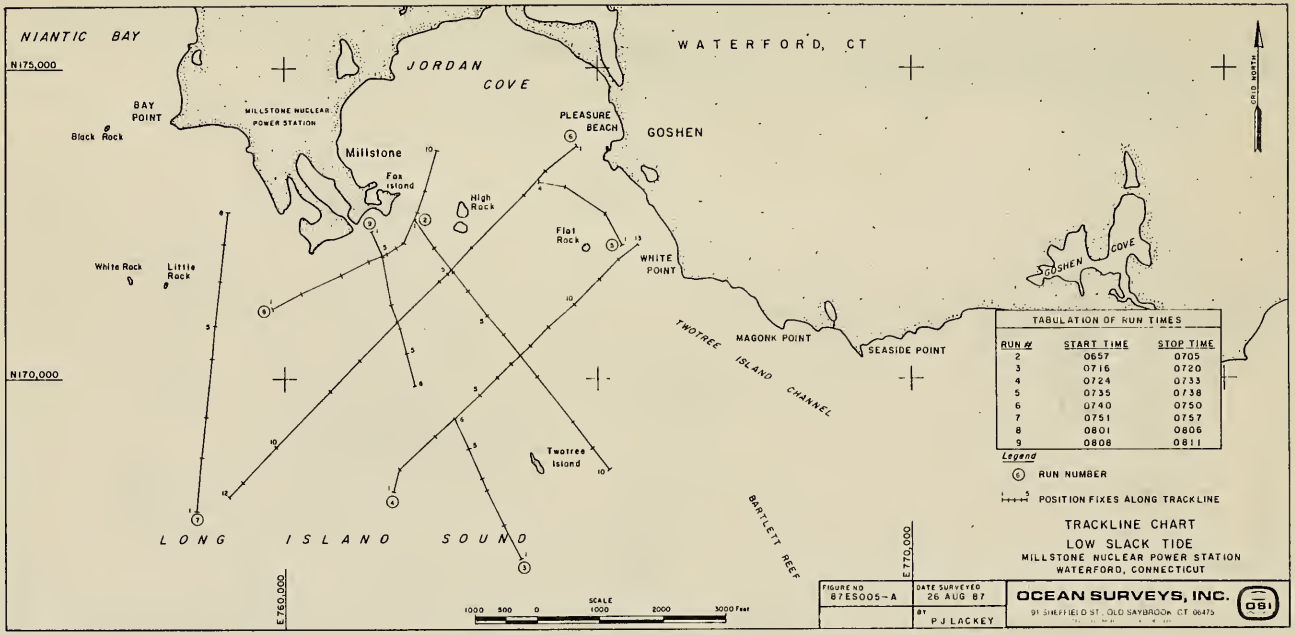
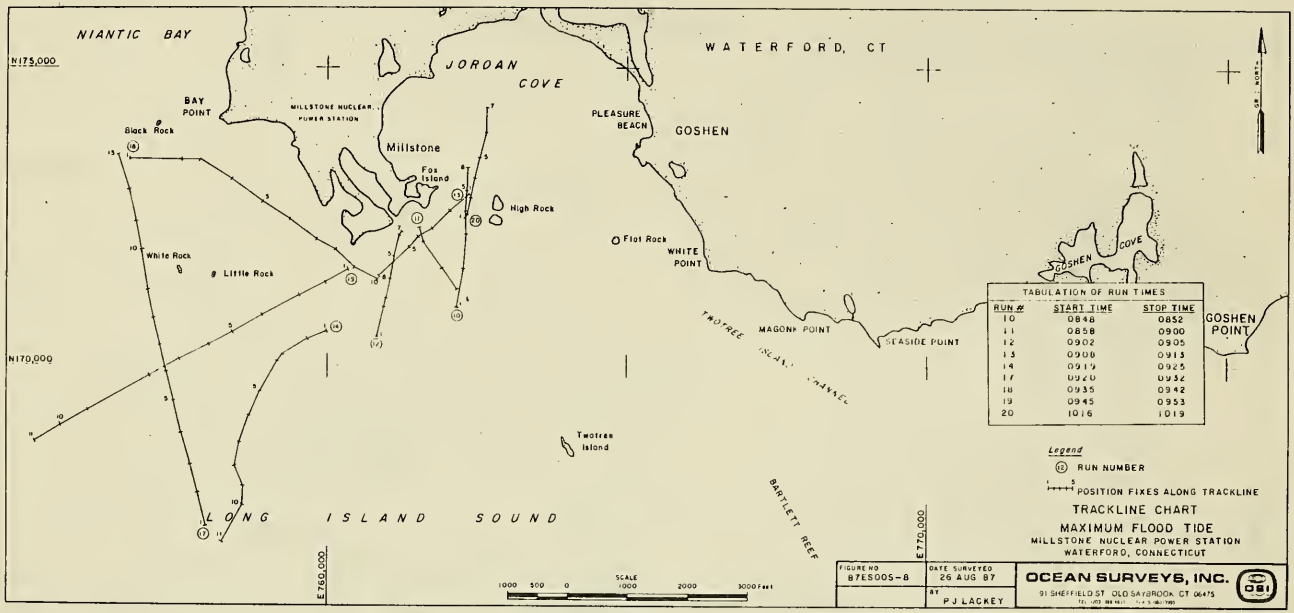
Appendix to Hydrothermal Studies


NIANTIC BAY
N175,000
N170,000
E760,000
E770,000
BAY POINT
Black Rock
MILLSTONE NUCLEAR POWER STATION
Millstone
JORDAN COVE
WATERFORD, CT
PLEASURE BEACH
GOSHEN
Fox Island
High Rock
Flat Rock
WHITE POINT
White Rock
Little Rock
GOSHEN COVE
MAGONK POINT
SEASIDE POINT
TWOTREE ISLAND CHANNEL
Twotree Island
BARTLETT REEF
LONG ISLAND SOUND
GRID NORTH
SCALE
1000 500 0 1000 2000 3000 Feet
TABULATION OF RUN TIMES
RUN # | START TIME | STOP TIME
2 | 0657 | 0705
3 | 0716 | 0720
4 | 0724 | 0733
5 | 0735 | 0738
6 | 0740 | 0750
7 | 0751 | 0757
8 | 0801 | 0806
9 | 0808 | 0811
Legend
RUN NUMBER
POSITION FIXES ALONG TRACKLINE
TRACKLINE CHART
LOW SLACK TIDE
MILLSTONE NUCLEAR POWER STATION
WATERFORD, CONNECTICUT
FIGURE NO 87ESOO5-A
DATE SURVEYED 26 AUG 87
BY P J LACKEY
OCEAN SURVEYS, INC.
91 SHEFFIELD ST., OLD SAYBROOK, CT 06475


NIANTIC BAY
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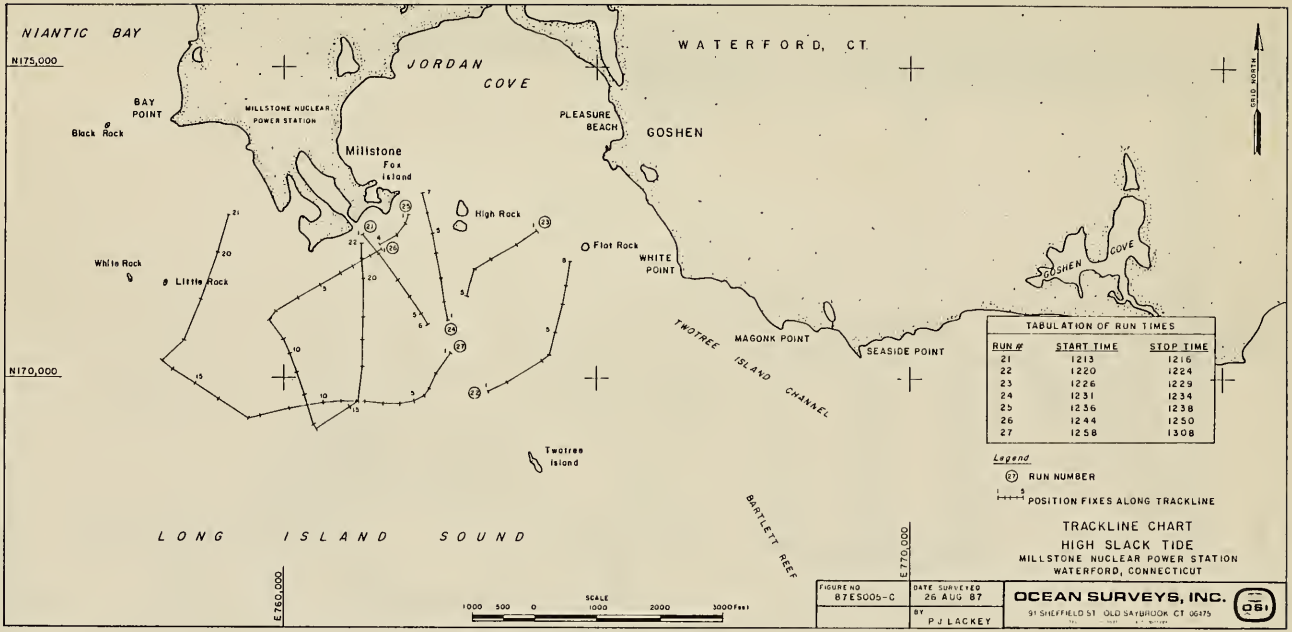
Flat Rock
WHITE POINT
GOSHEN COVE
GOSHEN POINT
MAGONK POINT
SEASIDE POINT
TWO TREE ISLAND CHANNEL
Twotree Island
BARTLETT REEF
LONG ISLAND SOUND
1000 500 0 SCALE 1000 2000 3000 Feet
TABULATION OF RUN TIMES
RUN # START TIME STOP TIME
10 0848 0852
11 0858 0900
12 0902 0905
13 0906 0913
14 0919 0925
17 0920 0932
18 0935 0942
19 0945 0953
20 1016 1019
Legend
(12) RUN NUMBER
5 POSITION FIXES ALONG TRACKLINE
TRACKLINE CHART
MAXIMUM FLOOD TIDE
MILLSTONE NUCLEAR POWER STATION
WATERFORD, CONNECTICUT
FIGURE NO 87ES005-8
DATE SURVEYED 26 AUG 87
BY PJ LACKEY
OCEAN SURVEYS, INC.
91 SHEFFIELD ST OLD SAYBROOK CT 06475
OSI


NIANTIC BAY
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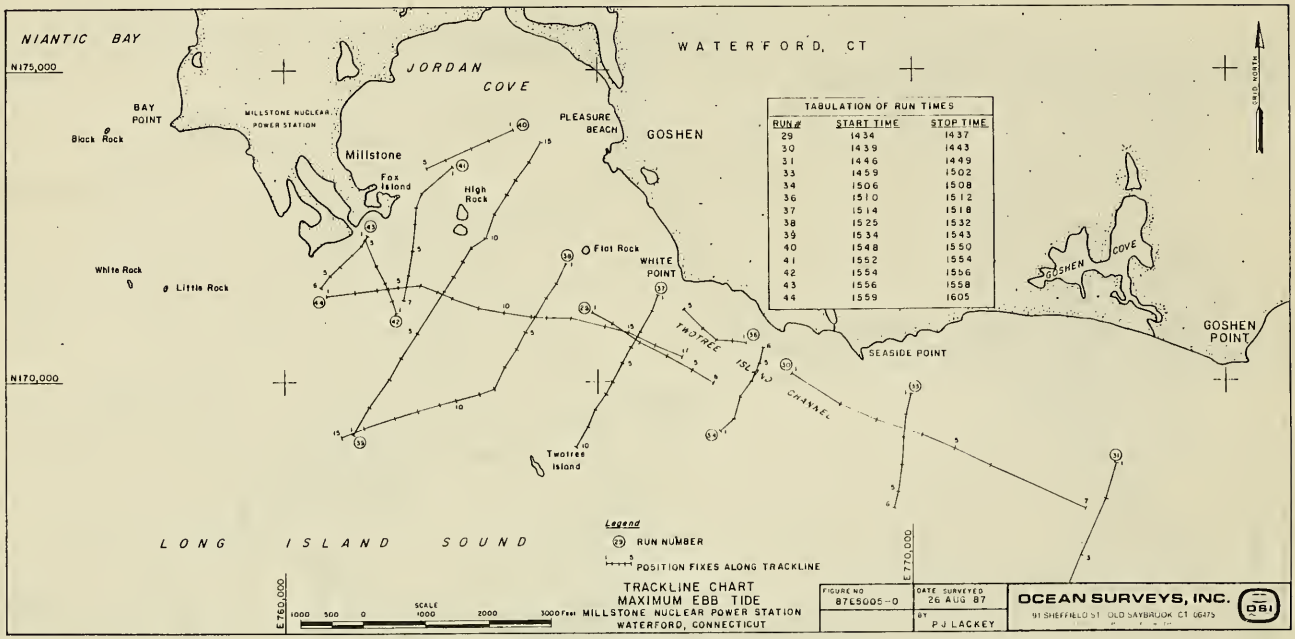
JORDAN COVE
WATERFORD, CT.
BAY POINT
Black Rock
MILLSTONE NUCLEAR POWER STATION
Millstone
Fox Island
PLEASURE BEACH
GOSHEN
High Rock
Flat Rock
WHITE POINT
White Rock
Little Rock
GOSHEN COVE
TWOTREE ISLAND CHANNEL
MAGONK POINT
SEASIDE POINT
Twotree Island
BARTLETT REEF
LONG ISLAND SOUND
GRID NORTH
SCALE
1000 500 0 1000 2000 3000 Feet
TABULATION OF RUN TIMES
RUN # START TIME STOP TIME
21 1213 1216
22 1220 1224
23 1226 1229
24 1231 1234
25 1236 1238
26 1244 1250
27 1258 1308
Legend
RUN NUMBER
POSITION FIXES ALONG TRACKLINE
TRACKLINE CHART
HIGH SLACK TIDE
MILLSTONE NUCLEAR POWER STATION
WATERFORD, CONNECTICUT
FIGURE NO 87ES005-C
DATE SURVEYED 26 AUG 87
BY P.J. LACKEY
OCEAN SURVEYS, INC.
91 SHEFFIELD ST OLD SAYBROOK CT 06475



TABULATION OF RUN TIMES

RUN #	START TIME	STOP TIME
29	1434	1437
30	1439	1443
31	1446	1449
33	1459	1502
34	1506	1508
36	1510	1512
37	1514	1518
38	1525	1532
39	1534	1543
40	1548	1550
41	1552	1554
42	1554	1556
43	1556	1558
44	1559	1605

Attachment to Hydrothermal Studies

FINAL REPORT

HYDROTHERMAL SURVEY

MILLSTONE NUCLEAR POWER STATION

WATERFORD, CONNECTICUT

Submitted To: Northeast Utilities Environmental Lab
PO Box 128
Waterford, CT 06385

Submitted By: Ocean Surveys, Inc.
91 Sheffield Street
Old Saybrook, CT 06475

30 September 1987

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II - Tabular Data

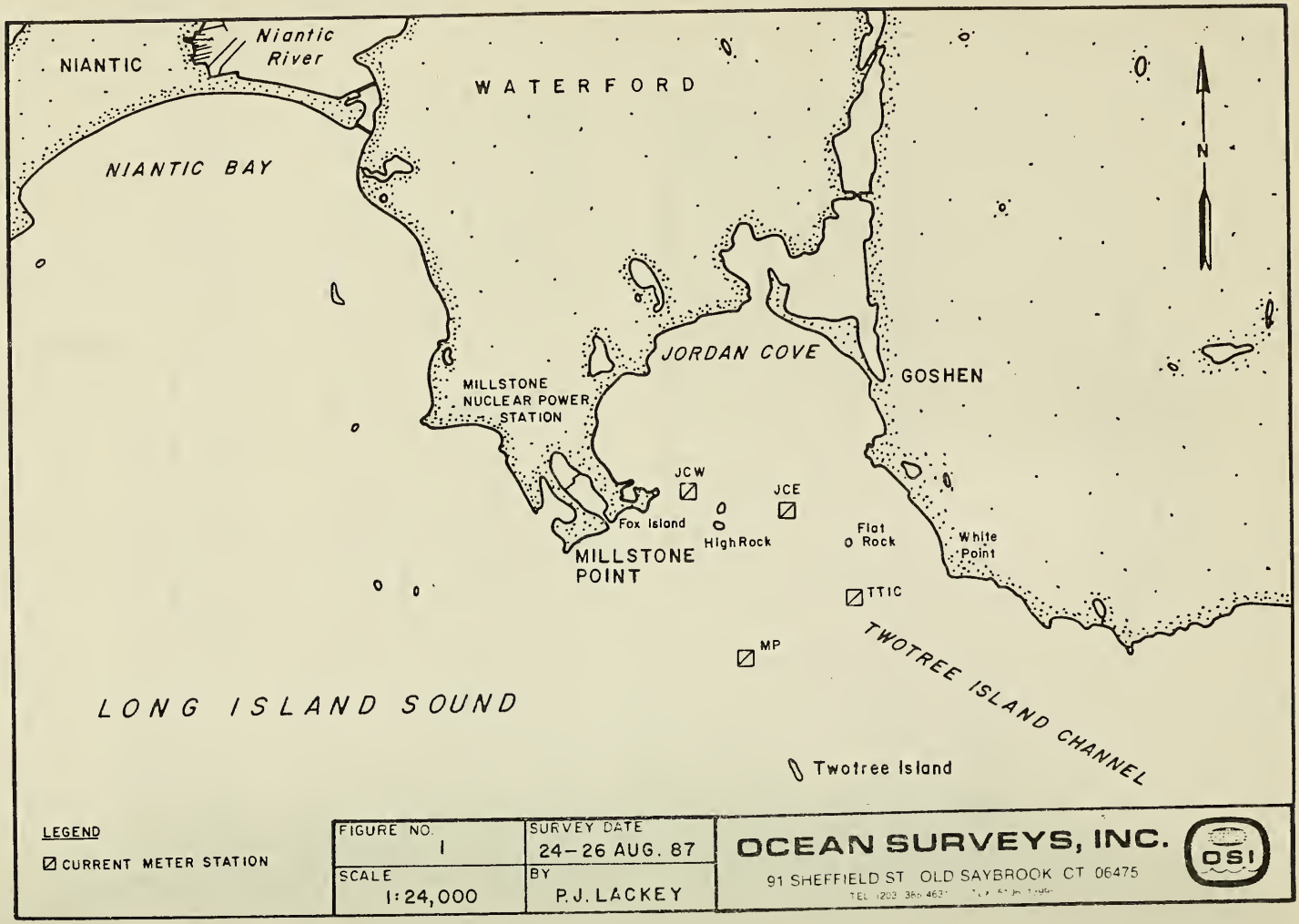
FINAL REPORT
HYDROTHERMAL SURVEY
MILLSTONE NUCLEAR POWER STATION
WATERFORD, CONNECTICUT

1.0 INTRODUCTION

During the period 21-26 August 1987, Ocean Surveys, Inc. (OSI) performed hydrographic and dye tracer surveys for Northeast Utilities Environmental Laboratory (NUEL) at the Millstone Nuclear Power Station, Waterford, Connecticut (Figure 1). This work was undertaken to provide NUEL with contoured delta-T isotherm maps of the generating station's thermal plume during four phases of a complete tidal cycle. NUEL assisted OSI in executing this project by supplying personnel, equipment and facilities for equipment monitoring and offshore surveying.

Rhodamine WT dye was injected into the Unit 3 discharge waters. Dye concentration and water temperature data were collected along 41 transects and 27 vertical profile stations in and around the thermal plume during the times of low slack, maximum flood, high slack, and maximum ebb tides. These data were analyzed to determine the positions of the 1.5^{o}, 4^{o}, 6^{o} and 8^{o} F delta-T isotherms. The contoured isotherms are presented by tidal phase in Figures 10 through 13 of this report.

Dye concentration and temperature data were additionally collected at the Unit 1 discharge well to monitor for the recirculation of power station cooling water and are presented in Figure 9 of this report.



LEGEND

☒ CURRENT METER STATION

FIGURE NO.	SURVEY DATE
1	24–26 AUG. 87
SCALE	BY
1:24,000	P.J. LACKEY

OCEAN SURVEYS, INC.
91 SHEFFIELD ST OLD SAYBROOK CT 06475
TEL (203) 388-4631

Background fluorescence, tide, salinity, temperature, and current speed and direction data were also collected prior to and during the dye concentration survey to support the development of the delta-T isotherm data. These data are presented in graphic form in Figures 4 through 8 and in tabular form in Appendix II.

A small circulation study employing free-drifting drogues at multiple depths was also conducted and the results are being held for later processing.

2.0 PROCEDURES AND EQUIPMENT

2.1 Horizontal Control

Horizontal control points easily discernible on 1:24,000 (1"=2,000') scale USGS Quadrangle maps were used as control stations for navigation equipment during the survey. The estimated accuracy of determining horizontal control point coordinates in this manner is ±50 ft in vessel locations relative to the Connecticut state grid system.

2.2 Vertical Control

OSI established a temporary tidal benchmark (TBM) at NUEL's dock facilities by correlating recorded tide levels with predicted tide elevations for Millstone Point (NOAA Tide Tables). The elevation of OSI's TBM is 5.2 ft Mean Low Water (MLW).

A Stevens Type F recording tide gauge was installed at the NUEL dock facilities and referenced to OSI's TBM. Tidal elevation data was continuously recorded during all survey operations. A specification for the Stevens Type F recording tide gauge is included in Appendix I.

2.3 Navigation

Survey vessel position data were acquired using OSI's "Maretrack" trackline control system in conjunction with a Cubic DM-40A "Autotape" electronic positioning system. OSI's "Maretrack" system consists of an Apple computer with video display and left/right indicator interfaced with the "Autotape" system. The "Autotape" system is comprised of three components: two shore-based range responders and an interrogator unit installed aboard the survey vessel. Range measurements to each responder are acquired from the phase comparison of microwave reference signals transmitted and received by the responders and the interrogator. The two ranges are automatically displayed in meters by the onboard interrogator and are updated at a one-second rate and input to the "Maretrack" system. The "Maretrack" program computes vessel location, distance to beginning of line, distance to end of line, vessel speed and cross-track (distance off intended survey trackline) error. Additionally, "Maretrack" indicates required course corrections in real-time through a left/right indicator.

In operation, the helmsman is able to locate the vessel's position with respect to the survey trackline on the video monitor. Once on line, he can steer the desired line following the course corrections indicated on the left/right display. All positional data are automatically recorded on a paper tape printer for later processing.

Where site conditions did not permit the use of the "Maretrack" system, an alternate positioning method was employed consisting of one range of the "Autotape" system and a theodolite established on NUEL's dock. The survey vessel was controlled along a bore sight representing the intended survey transect by the transit operator using a hand-held VHF

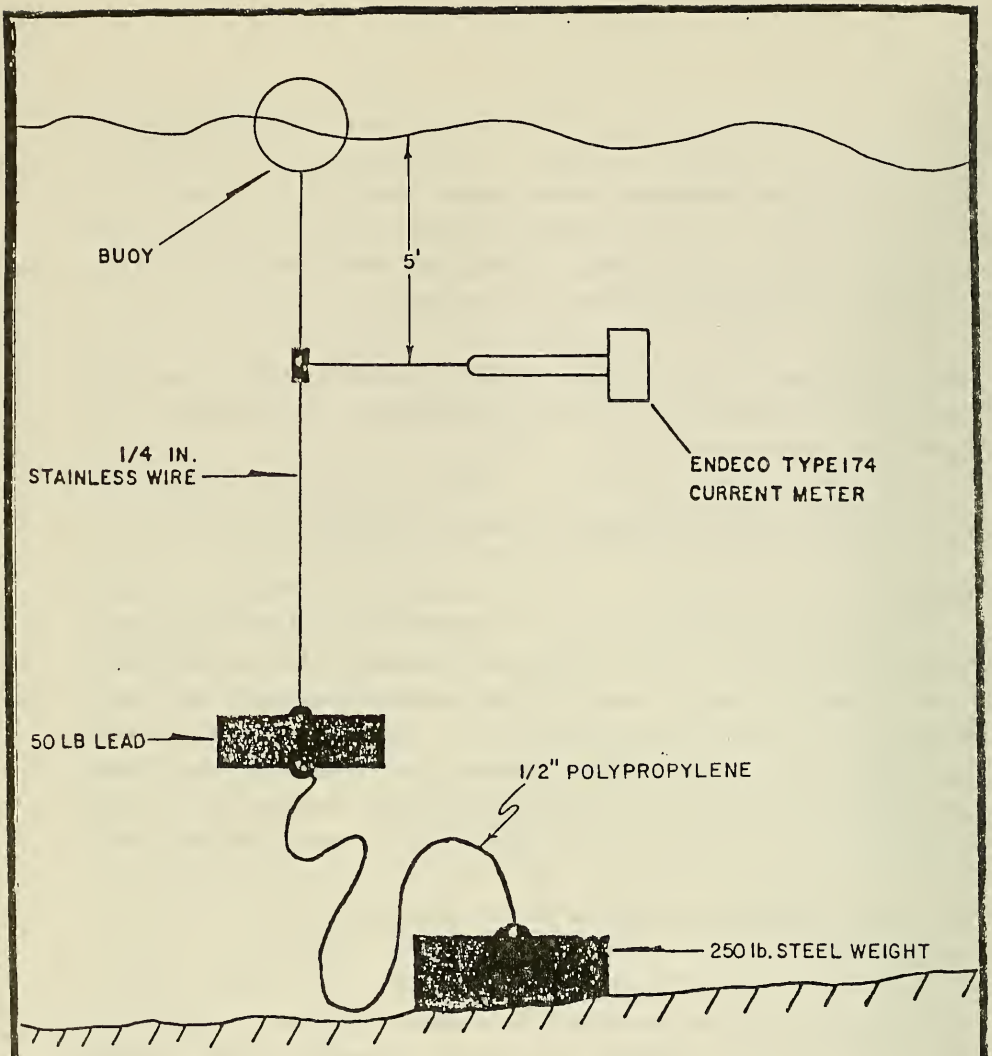
radio. Distance along the line was measured using the "Autotape" positioning system. Alternately, the helmsman steered a predetermined course while the transit operator turned angles from a known backsight. As above, all positional data were automatically recorded on paper tape with angles logged into the field notes.

Specification sheets for the "Autotape" system, the "Maretrack" system, and the theodolite are provided in Appendix I.

2.4 In Situ Current, Temperature, and Salinity Monitoring

Continuous measurements of current speed and direction, water temperature, and salinity were obtained by installing an Endeco Type 174 in situ recording current meter on each of two surface-following moorings deployed at stations east and southeast of Millstone Point (Figure 1). The meters were positioned 5 feet below the surface on a suspended taut line which was itself moored to the bottom (Figure 2). Two stations (JCE and JCW) were occupied on 24 and 25 August 1987 and two stations (TTIC and MP) were occupied on 26 August. Data was recorded in digital form on magnetic tape for later processing.

The Endeco type 174 instrument has been designed to eliminate the considerable effects of surface waves. The ducted impellor cancels the action of wave induced orbital velocities while a flexible tether decouples the instrument from mooring line motion. A specification sheet for the Endeco 174 current meter is included in Appendix I.



CURRENT METER MOORING DESIGN

FIGURE NO. 2	DATE 29 SEPT. 87	OCEAN SURVEYS, INC. OBI
SCALE N.T.S	BY P.J.L.	OLD SAYBROOK, CONNECTICUT

2.5 Dye Tracer Study

Dye dilution studies are based on the principle that the downstream dilution of a conservative substance is directly proportional to the mixing characteristics of the receiving water body. Temperature is assumed to be conservative in this study in that the temperature of the thermal plume is reduced only through mixing with Long Island Sound water. Dilution of Rhodamine WT dye injected into the thermal plume therefore is assumed to directly mimic the temperature reduction of the plume.

2.5.1 Dye Injection

Rhodamine WT dye is a fluorescent, biodegradable tracer that is extremely soluble in water and detectable in very small concentrations (less than 0.05 parts per billion). The dye was supplied as a 20 percent solution by Crompton and Knowles Corporation, Gibralter, Pennsylvania. The specific gravity of the individual lot of Rhodamine WT which OSI used at Millstone was 1.112 at 80^{o}F.

Dye was injected into the circulation water discharge well of Unit 3 utilizing a Fluid Metering, Inc. laboratory pump. The 20% solution of dye was pumped onto the surface of the discharge water. Mixing occured where the Unit 3 water entered the quarry and again where the waters from Units 1, 2, and 3 meet in the middle of the quarry. Dye injection began at 1500 hours on 23 August initially at a rate of 5 pounds per hour and was increased to 7 pounds per hour at approximately 1700 hours on 24 August 1987. Dye injection rates were monitored by weighing the dye supply reservoir at approximately one-hour intervals to an accuracy of $\pm$0.01 pounds. A specification sheet for the Fluid Metering, Inc. pump is included in Appendix I.

Vertical profiles of dye concentration were taken at three points across each of the two quarry cuts on 25 August to insure that complete mixing of the dye was occurring within the quarry. Dye concentration readings varied less than 0.05 ppb by weight indicating complete mixing.

2.5.2 Fluorescence Monitoring

Dye concentrations were monitored using Turner Designs Model 10 and Turner Associates Model 111 fluorometers. Both fluorometers provide a relative measure of the quantity of light emitted from a fluorescent solution. In principle, a lamp within the fluorometer emits light which is filtered and allowed to strike the sample as it flows continuously past the light source. Any dye present in the solution will fluoresce. The emitted light spectrum is passed through a secondary filter to a sensor, compared to the source light and the relative quantity of light is indicated by the fluorometer readout.

The fluorescence of dye varies with sample temperature; therefore, the water temperature in the sampling line was monitored with a Yellow Springs Instrument Company Series 700 thermistor to enable data processors to correct recorded dye concentrations for solution temperature. Both dye concentration and temperature were continuously recorded during all dye concentration surveys.

Turner Model 111 fluorometers equipped with thermistors and interfaced with Soltec two-pen strip chart recorders were installed at both the quarry cut and at the Unit 1 discharge well. The data from the instrument at the quarry cut was used to determine the concentration of dye in the discharge water for later processing of the thermal plume dye concentration data. Background fluorescence was also

recorded from 1700 hours, 21 August to 1400 hours, 22 August at the quarry cut to characterize fluctuations in the natural fluorescence of Long Island Sound waters. The instrument at the Unit 1 discharge well was used to monitor for the recirculation of cooling water.

Turner Model 10 fluorometers equipped with thermistors and interfaced with Soltec two-pen strip chart recorders were installed on the horizontal transect and the vertical profile boat.

Surficial dye concentrations and water temperatures were recorded along 41 transects during the four tidal mapping sessions. These transects were oriented nominally perpendicular to the axis of the thermal plume and along well defined plume boundaries. Dye concentrations and water temperature were also measured at 27 vertical profile stations to characterize the vertical mixing of the thermal plume.

Quarry cut dye concentrations were monitored from 1500 hours, 23 August until 1200 hours, 27 August including both the periods of dye buildup and flushing within the quarry. Buildup took 10 hours before the quarry cut concentrations stabilized at 2.2 ppb by weight. Similarly, it required 10 hours for concentration readings to stabilize after dye injection was stopped.

Pre- and post-survey calibrations of the fluorometers were conducted using standard solutions prepared with site water and dye drawn from the lot used for the study. These solutions were prepared employing Class A glassware which meets or exceeds National Bureau of Standards requirements. Water samples were also taken during the survey and used in the lab to verify instrument responses. Specification sheets

for the Turner Model 10 and 111 fluorometers, Yellow Springs Instrument Co. Series 700 thermistor, and the Soltec recorders are included in Appendix I.

3.0 DATA PROCESSING AND PRESENTATION

3.1 Survey Trackline Reconstruction

Survey tracklines were reconstructed from the "Autotape" ranges and transit angles logged at each position "fix." These values, together with the grid coordinates of the responder and theodolite locations, were input into OSI's DEC PDP 11/44 computer system which calculated the X and Y coordinates for each recorded position. During calculation of the vessel positions, geometric consideration of responder elevations, interrogator antenna height, X and Y corrections for sensor layback and offset (relative to the "Autotape" antenna), and range calibration data were also input to yield the most precise computation possible.

3.2 Tide Level Data

Half-hour water elevations taken from the continuous tide level chart recordings collected during the survey were referenced to the MLW datum and are presented graphically in Figure 3 and in tabular form in Appendix II.

3.3 In Situ Current, Temperature, and Salinity Data

The recorded current, temperature, and salinity data were translated employing an Endeco Type 250 data translator and input into OSI's in-house computer system for processing. Each data set was then corrected for the individual instrument calibration and computer plotted as time series plots. Data from the 24 and 25 August deployments at Station

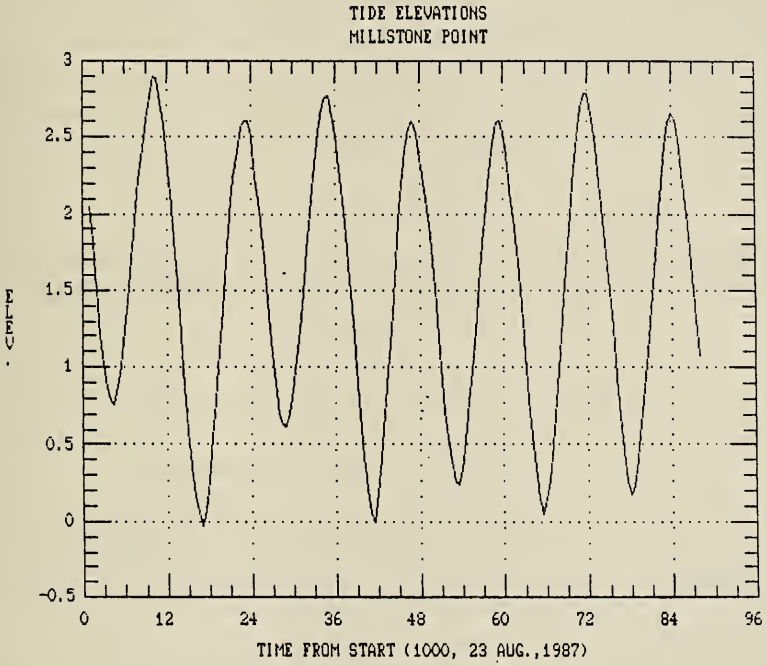


FIGURE NO. 3	DATE 9/29/87	OCEAN SURVEYS, INC.	OSI
SCALE NA	BY JAH	OLD SAYBROOK, CONNECTICUT	

JCE are presented on Figure 4 and Station JCW on Figure 5. Data collected on 26 August at Stations TTIC and MP are presented on Figures 6 and 7, respectively. These data are also presented in tabular form in Appendix II.

3.4 Dye Concentration Data

Dye concentration data recorded on strip chart must be converted from fluorescence readings to dye concentrations in parts per billion (ppb) by weight. This was accomplished by first correcting the fluorescence data to a standard temperature according to the equation:

$$CONC_{TRUE} = CONC_{REC} \times e^{0.015(T_R - T_S)}$$

where, $CONC_{TRUE}$ = dye concentration corrected for sample temperature

$CONC_{REC}$ = recorded fluorometer output

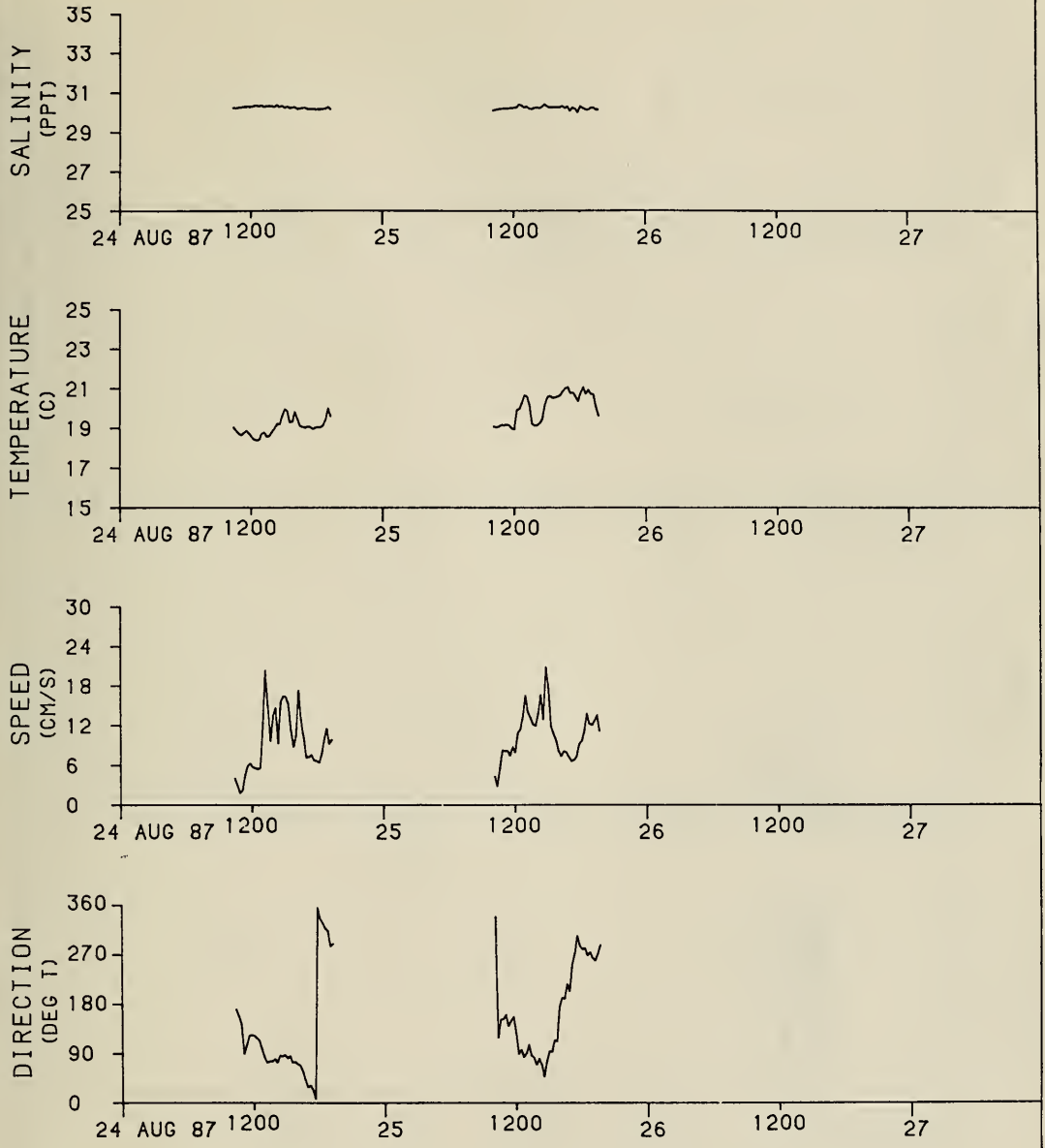
T_R = recorded sample temperature

T_S = standard temperature; in this case, $T_S = 68^{o}F$

Using calibration data for each fluorometer and the specific gravity of the dye lot, the "equivalent" dye concentration was calculated in ppb by weight.

3.5 Background and Recirculation

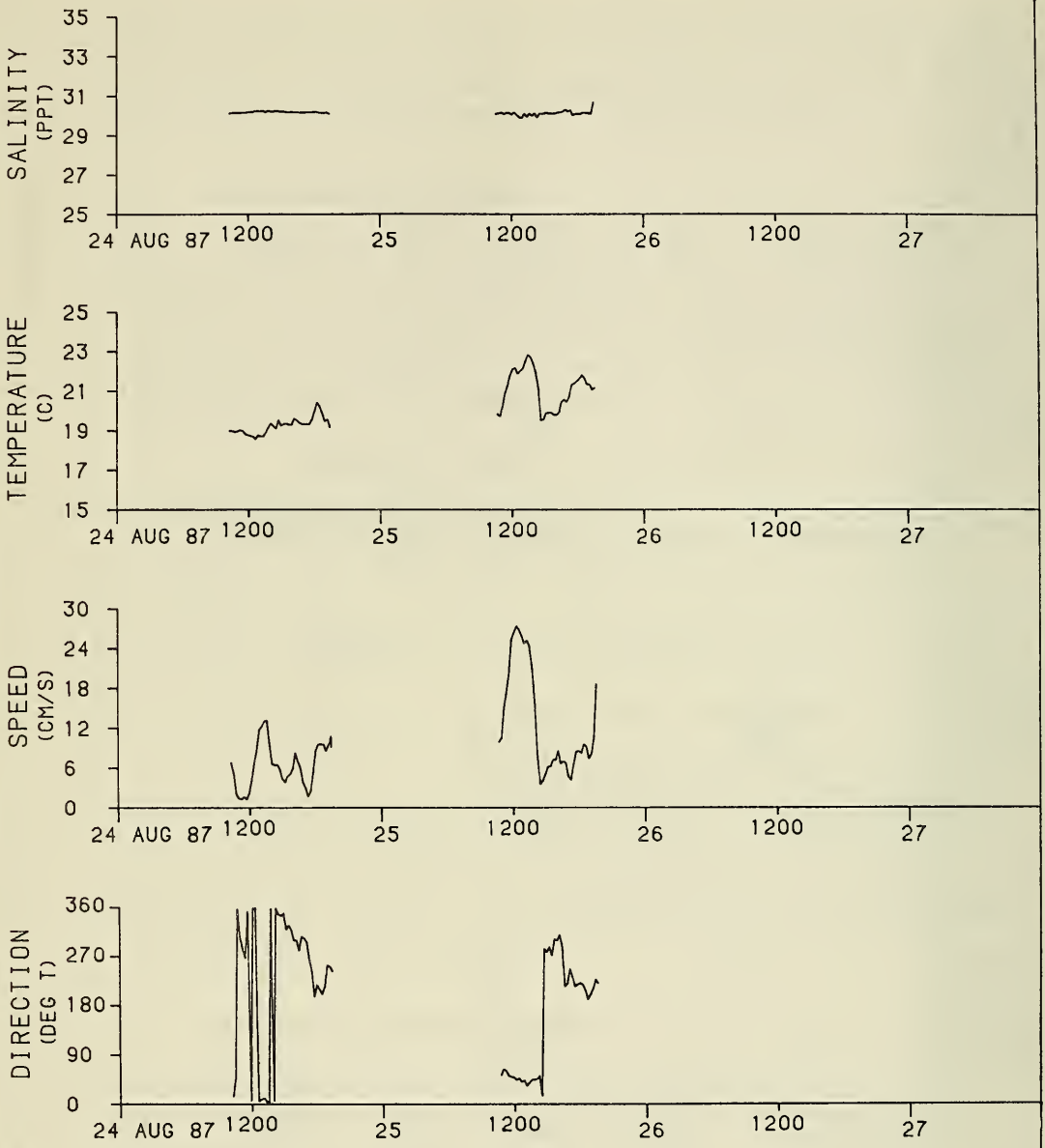
Dye concentration data from the background fluorescence instrument at the quarry cut and the Unit 1 recirculation fluorometer were processed as above and are presented as time series plots in Figures 8 and 9.



SURVEY DATE
24–25 AUG. 87

JORDAN COVE, NIANTIC
STATION – JCE
Figure No. 4

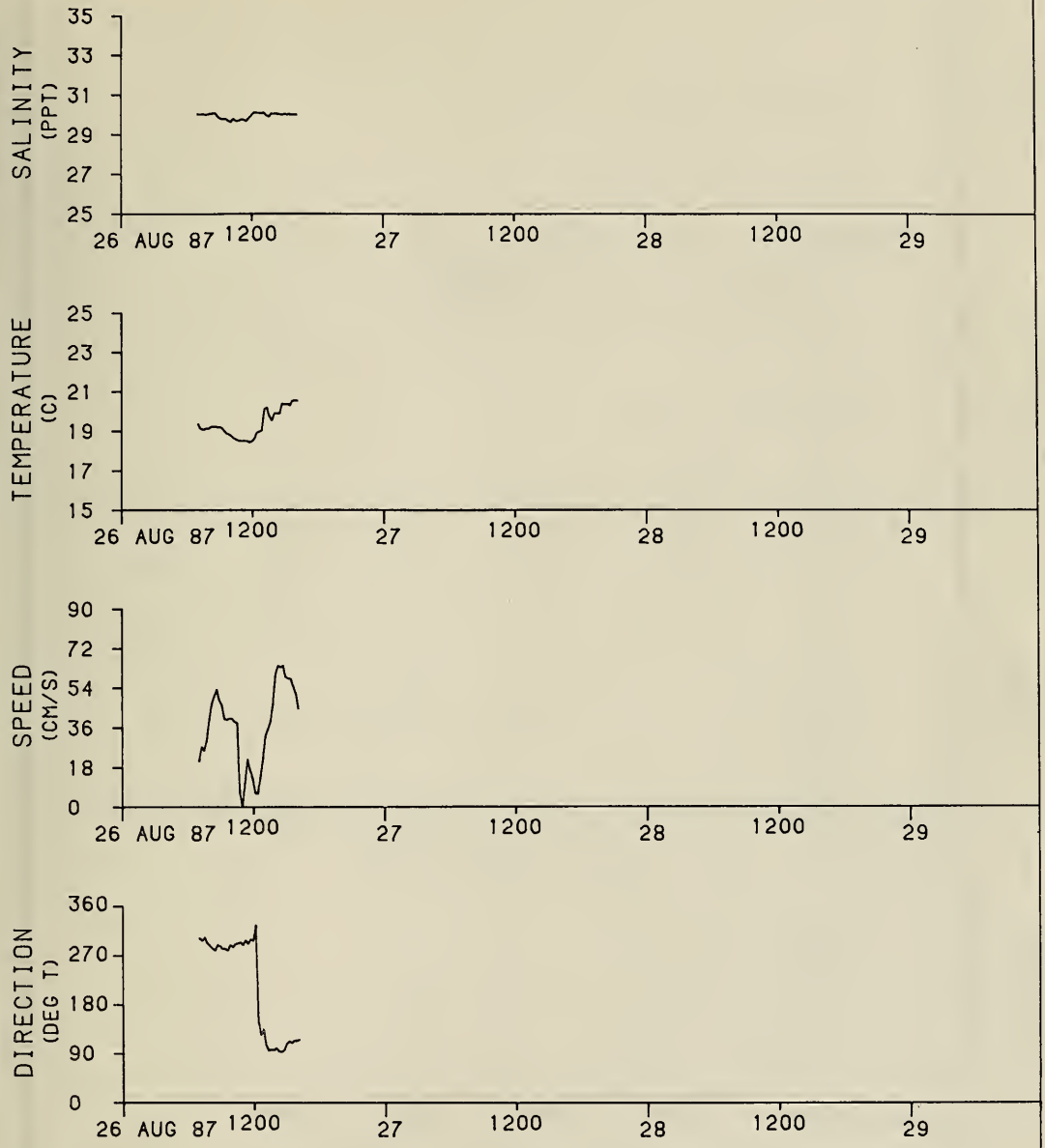
OCEAN SURVEYS, INC.
91 SHEFFIELD ST., OLD SAYBROOK, CT 06475
TEL (203) 388-4631 TLX 5106013995



SURVEY DATE
24–25 AUG. 87

JORDAN COVE, NIANTIC
STATION–JCW
Figure No. 5

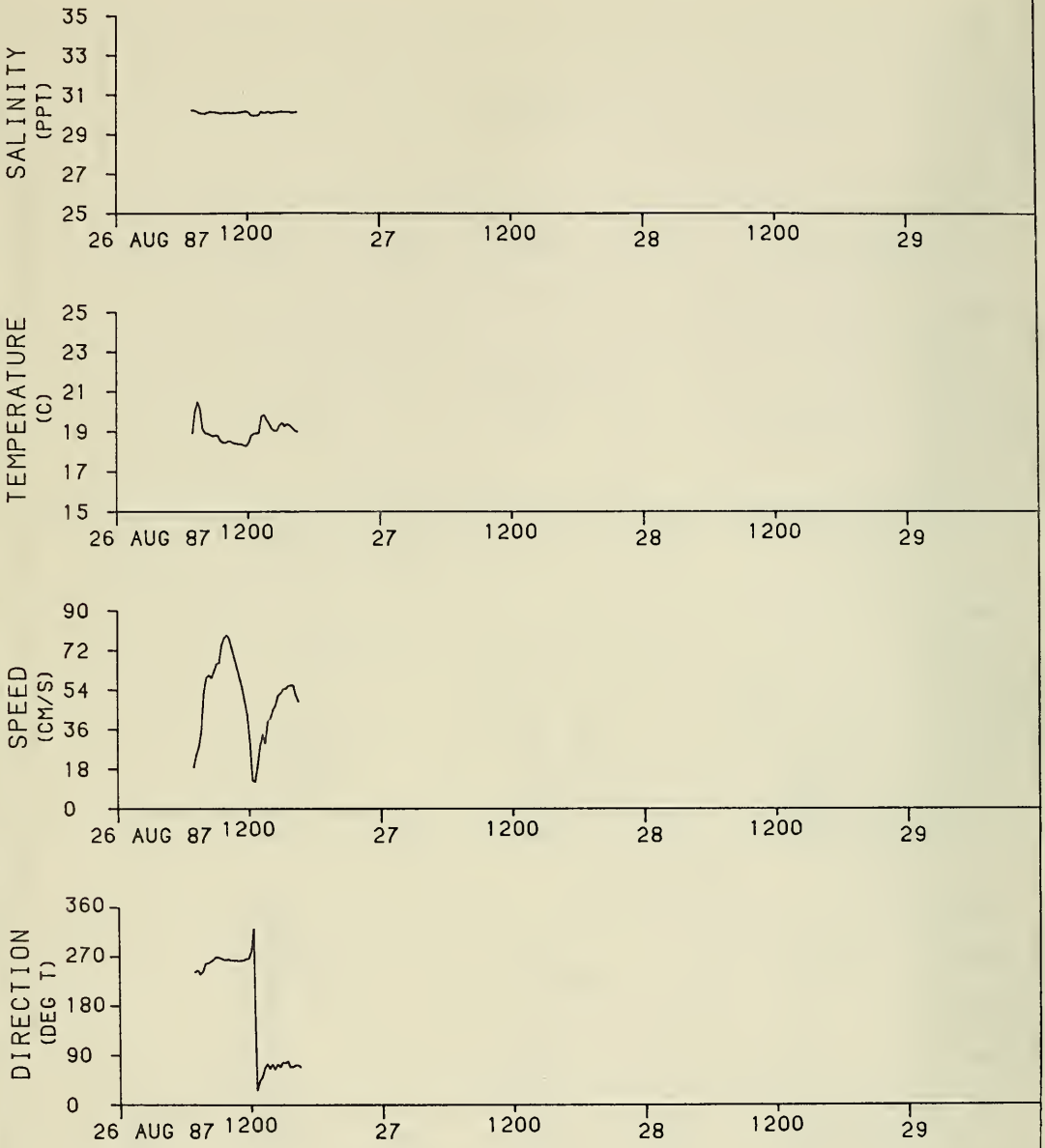
OCEAN SURVEYS, INC.
91 SHEFFIELD ST., OLD SAYBROOK, CT 06475
TEL (203) 388-4631 TLX 5106013995



SURVEY DATE
26 AUG. 87

TWOTREE ISLAND CHANNEL, NIANTIC
STATION – TTIC
Figure No. 6

OCEAN SURVEYS, INC.
91 SHEFFIELD ST., OLD SAYBROOK, CT 06475
TEL (203) 388-4631 TLX 5106013995



SURVEY DATE
26 AUG. 87

MILLSTONE POINT, NIANTIC
STATION — MP
Figure No.7

OCEAN SURVEYS, INC.
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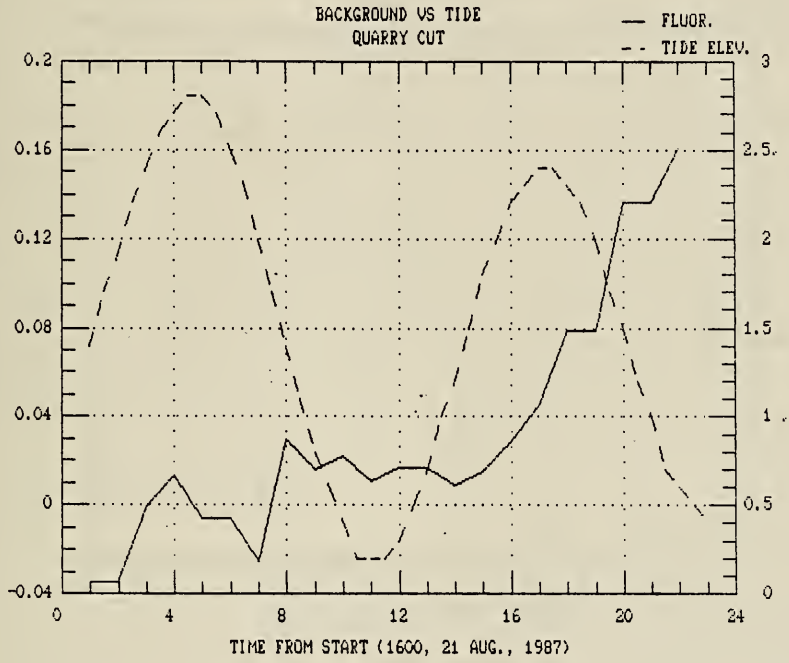


FIGURE NO. 8	DATE 9/29/87	OCEAN SURVEYS, INC. OSI
SCALE NA	BY JAH	OLD SAYBROOK, CONNECTICUT

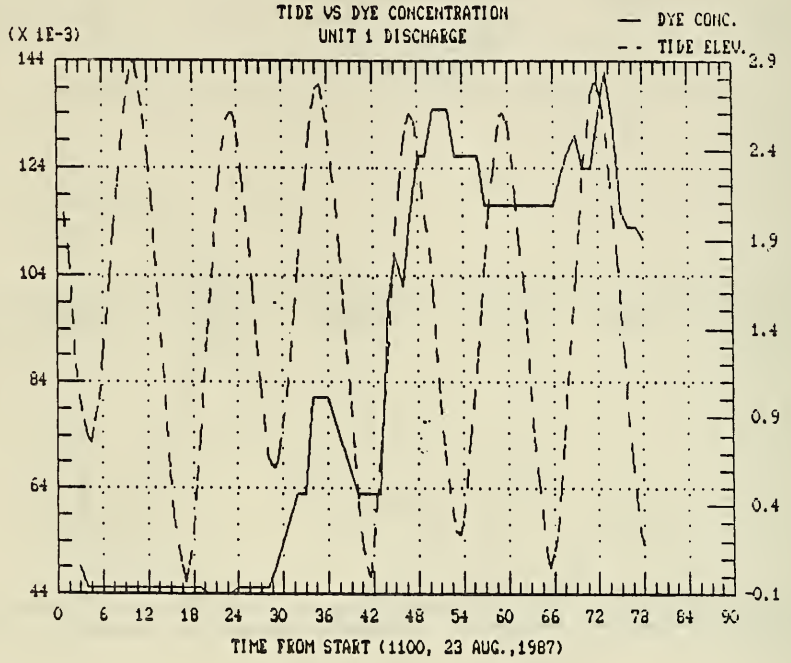


FIGURE NO. 9	DATE 9/29/87	OCEAN SURVEYS, INC.
SCALE NA	BY JAH	OLD SAYBROOK, CONNECTICUT

3.6 Isothermal Data

Since both dye concentration and water temperature are held to be convervative, the percent drop in the temperature of the plume with respect to the total temperature difference between the discharge water and the receiving body of water is equal to the percent dilution of the dye in the plume with respect to the dye concentration of the discharge water at the quarry cut. Dye concentrations in ppb by weight were converted to degrees Farenheit above ambient temperature and plotted on a trackline map for each survey. These data were contoured at the 1.5^{o}, 4^{o}, 6^{o} and 8^{o}F delta-T levels and are presented on Figures 10 through 13. Data from the vertical profiles at increasing distances from the quarry cut along the axis of the plume were also developed and plotted as delta-T versus depth. These profiles are presented on Figures 14 through 17. Additional vertical profiles not associated with the axis of the plume are also presented on Figures 14 through 17.

4.0 DISCUSSION OF DATA

4.1 Background Fluorescence

Prior to initiating dye injection, the natural or background fluorescence of the circulation water was recorded at the quarry cut on Millstone Nuclear Power Station. Tide elevations were also measured from 1700 hours, 21 August to 1400 hours, 22 August, 1987 and are presented together with the background fluorescence data on Figure 8. The background fluorescence remains near zero for the first 14 hours of the study. From 0700, 22 August the background fluorescence is seen to rise, coinciding with a storm event which occurred that day. The increase in fluorescence may represent the presence of naturally fluorescent material introduced into

the water by a combination of sea state and meteorological conditions. Background fluorescence had returned to pre-storm levels by the time dye injection began on 23 August.

No correlation is found between tidal phase and background fluorescence as has been observed on similar surveys conducted by OSI.

4.2 Current, Temperature, and Salinity Data

In situ recording current meters were installed at Stations JCE and JCW (Figure 1) for approximately 10 hours each on 24 and 25 August. These data were collected to characterize the tidal currents and associated temperature and salinity at the entrance to Jordan Cove to the east of Millstone Point (Figures 4 and 5).

As indicated on Figure 4, a well defined NNE-SSW trending tidally driven current is developed between Fox Island and High Rock. Similarly, Figure 5 shows an ENE-SW tidal current developed between High Rock and Flat Rock. Flood tidal currents to the NNE and ENE have a greater speed than the SSW and SW ebb currents. Water temperatures on the flood tide tend to be lower than the ebb tide, representing the difference between Long Island Sound/Block Island Sound water and water which has been heated in relatively shallow Niantic Bay and Jordan Cove. Salinities remain relatively constant indicating no significant influx of fresh water runoff or excessive evaporation.

To augment the dye concentration survey, recording current meters were deployed at Station TTIC in Twotree Island Channel off White Point and at Station MP directly off Millstone Point on 26 August. Millstone Point data (Figure

7) indicates a well defined E-W tidal current system with westerly flood tidal currents having a greater peak speed than the easterly ebb currents.

Temperature and salinity at Station MP are relatively constant due to the station's location in Long Island Sound. Short duration thermal peaks appear to be associated with periods of slack currents. These peaks probably represent the influence of the thermal plume from Millstone Point as it reaches further offshore during times of tidal current reversal. Station MP does map inside the 1.5^{o} isotherm during high slack tide (Figure 12) and inside the 4^{o} isotherm during low slack tide (Figure 10).

Data from the Twotree Island Channel station (TTIC) (Figure 6) show the tidal currents are WNW-ESE in direction. Peak ebb current speeds to the ESE are greater than the flood current, possibly due to the flow being restricted between the mainland to the north and Bartlett's reef to the south.

The temperature of the ebb currents are approximately $2\text{-}4^{o}$F greater than the flood currents. This difference is too great to be due only to thermal plume water being carried down the channel. Thermal mapping discussed later in this report indicates that only $1.5\text{-}2^{o}$F can be attributed to the thermal plume. The additional temperature difference is probably attributable to cooler waters from Block Island Sound brought in on the flood tide. Mixing with warmer Long Island Sound water would serve to raise water temperatures for the subsequent ebb tide.

The recorded times of low slack tide and maximum flood currents for Twotree Island Channel are within a half-hour of predicted times but actual times of high slack tide and maximum ebb currents are up to 1.75 hours later than

predicted. The recorded times of current reversal and maximum currents at Station MP are approximately 1 hour later than at Station TTIC.

4.3 Isothermal Data

Dye concentration data were collected along 41 tracklines and 27 vertical profiles during the 4 major tidal phases on 26 August. These data were converted to degrees Fahrenheit above ambient water temperatures, contoured at 1.5^{o}, 4^{o}, 6^{o}, and 8^{o} delta-T isotherms and are presented on Figures 10 through 13 and as vertical profiles on Figures 14 through 17. The term "delta-T isotherm" will be abbreviated to simply "isotherm" for the remainder of this report.

The dye concentration mapping was conducted under nearly ideal weather conditions. Seas were calm (less than 1 ft), reducing thermal plume mixing due to wave action to a minimum. The light winds, averaging 2 meters per second, assures that the dispersal of the thermal plume was due predominantly to tidal influences. Conditions were good enough to allow surface expressions of the plume boundaries to be observed during the maximum flood, high slack, and maximum ebb stages of the tide.

A further benefit of the good survey conditions is the development of the 1.5^{o} isotherm. Greater wind and wave action would have diminished the lateral extent of this isotherm. As it was, error-free equipment operation combined with excellent site conditions to allowed for clear definition of the 1.5^{o} isotherm.

4.3.1 Low Slack

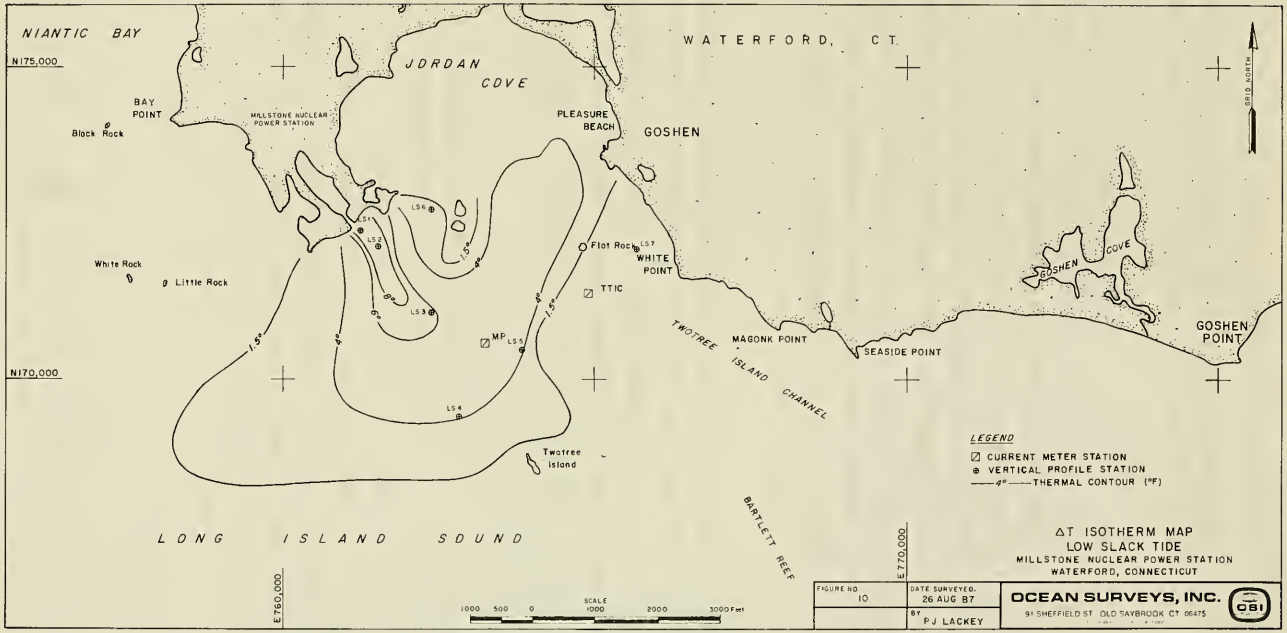
The low slack isotherm map shown on Figure 10 indicates the thermal plume is fairly well distributed about the discharge point at the quarry cut on Millstone Point. The 4^{o} isotherm extends up to 3500' directly off the quarry cut and continues around to the north into the eastern portion of Jordan Cove. The 6 and 8^{o} isotherms define the edges of the jet itself. The vertical profiles (Figure 14) along the axis of the plume show that the 4^{o} isotherm extends to the bottom up to 500' from the quarry cut (Stations LS1 and LS2). At 2,000' feet from the quarry cut (Station LS3), the base of the thermal plume is 10'-15' below the surface as indicated by the 1.5^{o} isotherm. A similar trend is observed on Profiles LS4 and LS5 3500' off the quarry cut.

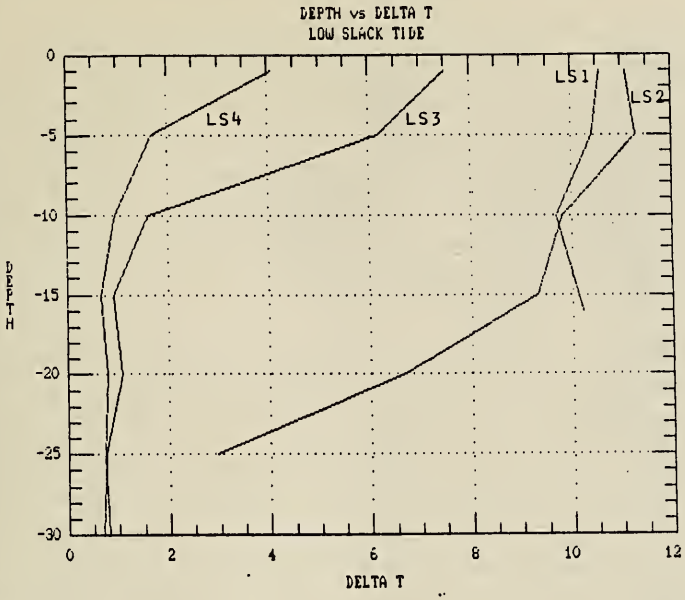
The vertical profile located in the western entrance to Jordan Cove (LS6) indicates a relatively high delta-T at the surface which is not supported by horizontal transect data. This station was sampled at the start of the low slack tide mapping session and probably represents a remnant of the previous maximum ebb tide.

Similarly, the 1.5^{o} delta-T observed throughout the water column at Station LS7 also represents the influence of the preceeding ebb tide. Since horizontal transect data collected just offshore from this station recorded delta-T's of less than 1.5^{o}, Station LS7 was probably located in an isolated remnant of ebb tide waters trapped against the shore.

4.3.2 Maximum Flood

During the maximum flood tidal stage (Figure 11) strong currents carry the thermal plume to the west. Mixing dilutes the plume so that the 4^{o} isotherm extends a maximum of 2,000'


NIANTIC BAY
N175,000
JORDAN COVE
WATERFORD, CT.
BAY POINT
Black Rock
MILLSTONE NUCLEAR POWER STATION
PLEASURE BEACH
GOSHEN
GRID NORTH
LS1
LS2
LS3
LS4
LS5
LS6
LS7
Flat Rock
WHITE POINT
White Rock
Little Rock
TTIC
MP
GOSHEN COVE
TWOTREE ISLAND CHANNEL
MAGONK POINT
SEASIDE POINT
GOSHEN POINT
N170,000
Twotree Island
BARTLETT REEF
LONG ISLAND SOUND
E760,000
E770,000
SCALE
1000 500 0 1000 2000 3000 Feet
LEGEND
CURRENT METER STATION
VERTICAL PROFILE STATION
4° THERMAL CONTOUR (°F)
ΔT ISOTHERM MAP
LOW SLACK TIDE
MILLSTONE NUCLEAR POWER STATION
WATERFORD, CONNECTICUT
FIGURE NO. 10
DATE SURVEYED. 26 AUG 87
BY P.J. LACKEY
OCEAN SURVEYS, INC.
91 SHEFFIELD ST OLD SAYBROOK CT 06475
OSI



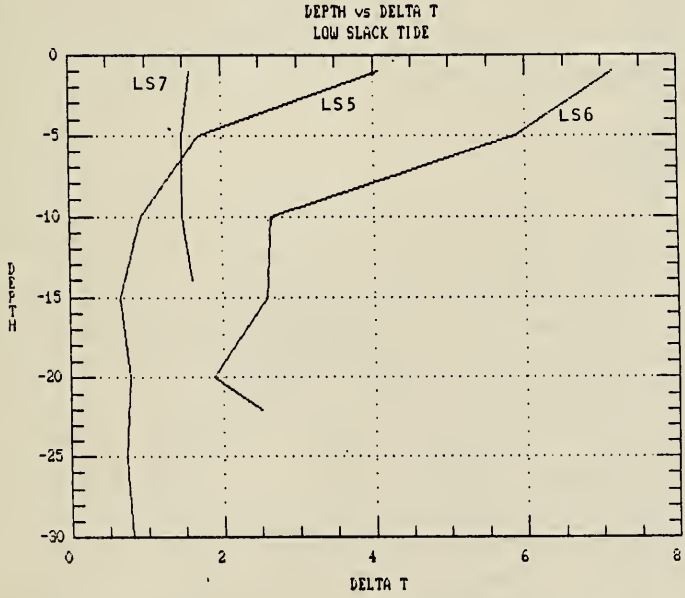


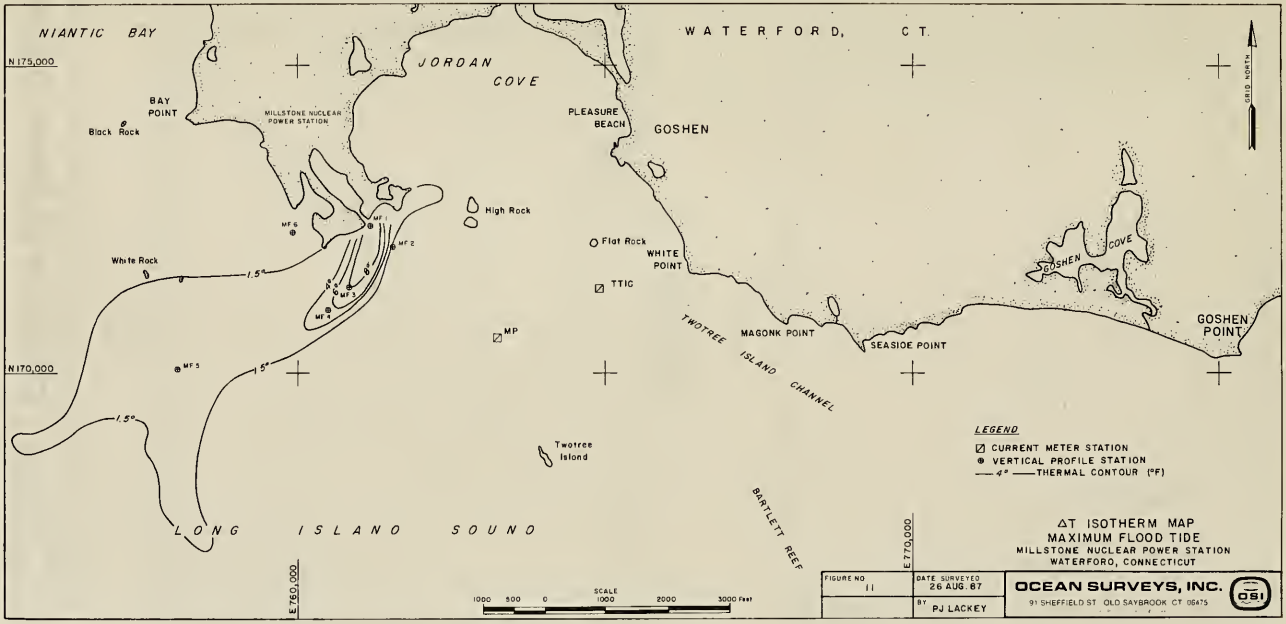
FIGURE NO. 14	DATE 9/29/87	OCEAN SURVEYS, INC.	
SCALE NA	BY JAH	OLD SAYBROOK, CONNECTICUT	OSI

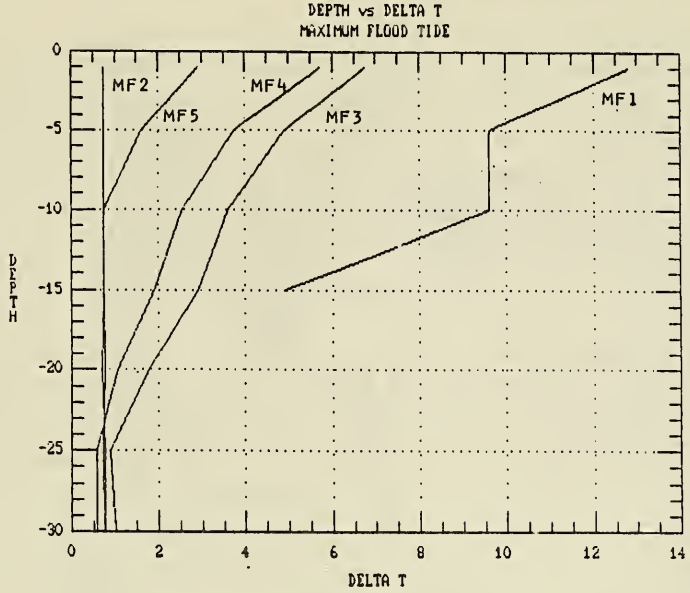
to the west in a narrow tongue. The 1.5° isotherm is observed much farther to the west where it appears to begin separating into multiple branches. A well defined eastern edge to the plume as defined by a change in surface water texture and a line of foam on the surface was observed in the field. Dye concentration readings dropped to background levels as this line was crossed.

Vertical profiles (Figure 15) through the plume show the 4° isotherm extends to the bottom at Station MF1 but is at less than 10' deep further out in the plume at Stations MF3 and 4. At Station MF5 south of White Rock, the base of the plume is only 5' deep as indicated by the 1.5° isotherm. Station MF2 was located to the east of the visible plume edge and recorded background levels only. Station MF6 located to the west of Millstone Point indicates a trace of the plume at the surface. This was not seen on the horizontal mapping data and is believed to represent the effects of a minor eddy on the northern edge of the plume.

4.3.3 High Slack

During high slack tide (Figure 12) the thermal plume is relatively evenly distributed about the discharge point and the center of the plume is shorter and broader than seen on previous tidal phases. This difference between the core of the high slack plume and the longer, narrower core of the low slack plume is probably due to the change in tide elevations. During low slack tide the elevation difference between the quarry cut and Long Island Sound is greatest, producing higher discharge currents at the cut than during high slack tide. The greater currents would tend to carry the plume jet further offshore. Lower current speeds during high slack tide would allow the plume jet to spread out more quickly, producing the shorter, broader pattern observed. The 4°


NIANTIC BAY
WATERFORD, CT.
JORDAN COVE
N 175,000
BAY POINT
Black Rock
MILLSTONE NUCLEAR POWER STATION
PLEASURE BEACH
GOSHEN
GRID NORTH
High Rock
MF 6
MF 1
MF 2
MF 4
MF 3
White Rock
Flat Rock
WHITE POINT
TTIC
GOSHEN COVE
MP
TWOTREE ISLAND CHANNEL
MAGONK POINT
SEASIDE POINT
GOSHEN POINT
N 170,000
MF 5
1.5°
5°
Twotree Island
LONG ISLAND SOUND
BARTLETT REEF
E 760,000
E 770,000
1000 500 0 SCALE 1000 2000 3000 Feet
LEGEND
CURRENT METER STATION
VERTICAL PROFILE STATION
4° THERMAL CONTOUR (°F)
ΔT ISOTHERM MAP
MAXIMUM FLOOD TIDE
MILLSTONE NUCLEAR POWER STATION
WATERFORD, CONNECTICUT
FIGURE NO 11
DATE SURVEYED 26 AUG. 87
BY PJ LACKEY
OCEAN SURVEYS, INC.
91 SHEFFIELD ST OLD SAYBROOK CT 06475
OSI



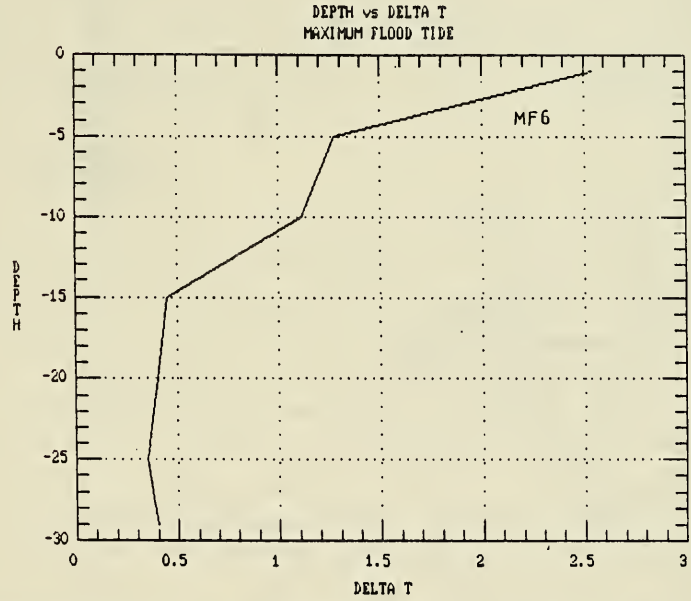
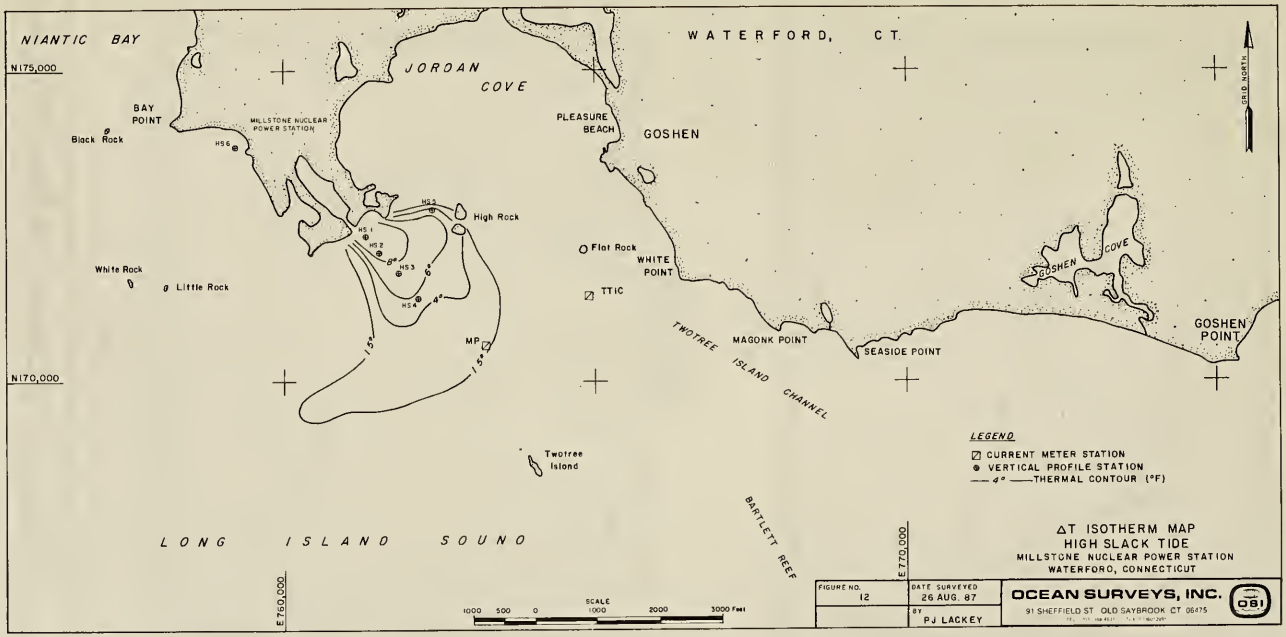
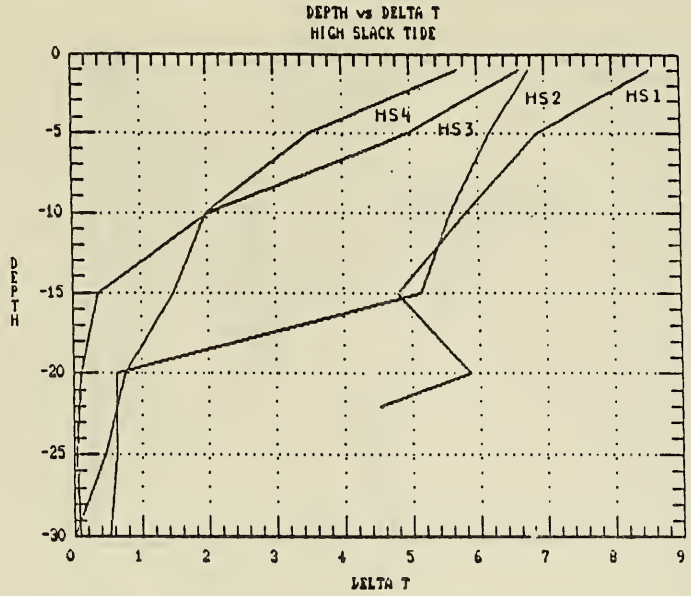


FIGURE NO. 15	DATE 9/29/87	OCEAN SURVEYS, INC.
SCALE NA	BY JAH	OLD SAYBROOK, CONNECTICUT


NIANTIC BAY
N175,000
N170,000
E760,000
E770,000
JORDAN COVE
WATERFORD, CT.
BAY POINT
Black Rock
MILLSTONE NUCLEAR POWER STATION
HS6
HS5
HS1
HS2
HS3
HS4
High Rock
PLEASURE BEACH
GOSHEN
Flat Rock
WHITE POINT
TTIC
White Rock
Little Rock
MP
15'
6'
4'
TWOTREE ISLAND CHANNEL
MAGONK POINT
SEASIDE POINT
GOSHEN COVE
GOSHEN POINT
GRID NORTH
Twotree Island
BARTLETT REEF
LONG ISLAND SOUND
SCALE
1000 500 0 1000 2000 3000 Feet
LEGEND
CURRENT METER STATION
VERTICAL PROFILE STATION
—4°— THERMAL CONTOUR (°F)
ΔT ISOTHERM MAP
HIGH SLACK TIDE
MILLSTONE NUCLEAR POWER STATION
WATERFORD, CONNECTICUT
FIGURE NO. 12
DATE SURVEYED 26 AUG. 87
BY PJ LACKEY
OCEAN SURVEYS, INC.
91 SHEFFIELD ST. OLD SAYBROOK CT 06475
OSI



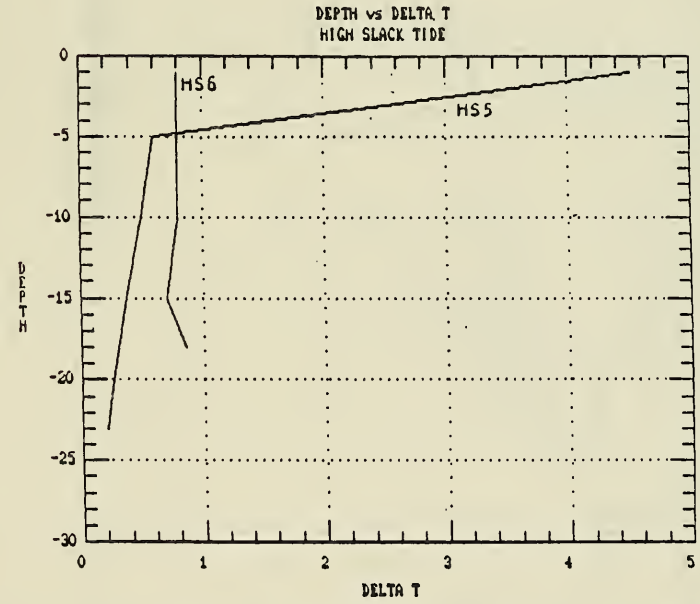


FIGURE NO. 16	DATE 9/29/87	OCEAN SURVEYS, INC.
SCALE NA	BY JAH	OLD SAYBROOK, CONNECTICUT

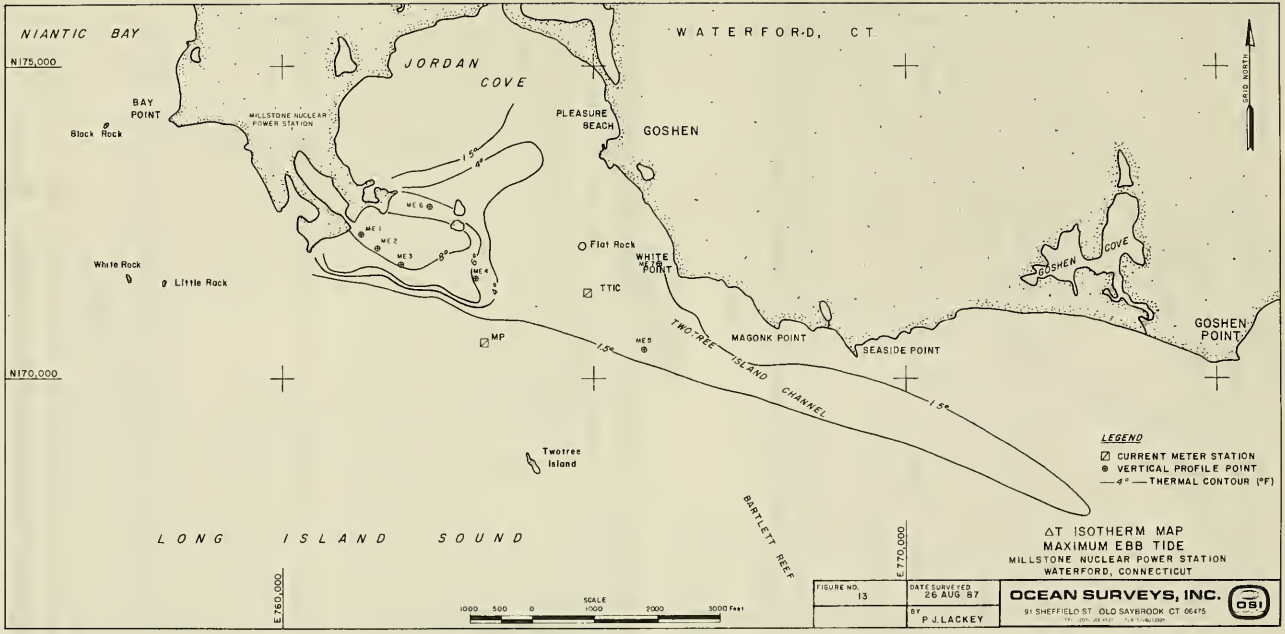
isotherm extends up to 2,100' offshore while the 1.5^{0} isotherm is approximately 3,000' off the cut. An extension of the 1.5^{0} isotherm to the west is probably a remnant of the previous flood tide.

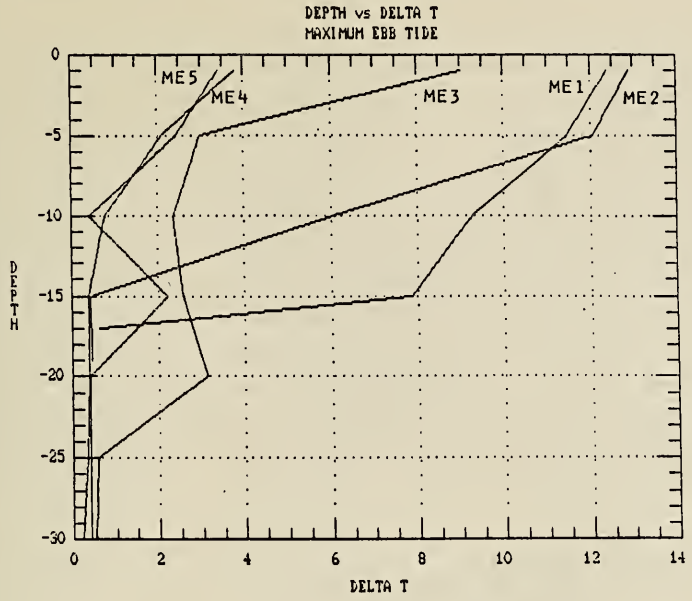
Vertical profiles (Figure 16) indicate the base of the plume close to shore is approximately 20' deep and decreases to about 10' beyond 1,000 feet from shore. Station HS5 in Jordan Cove shows the base of the plume to be quite shallow; less than 5' deep. Station HS6 located off the Unit 1 intake shows no major influence from the thermal plume. A small amount of dye was detected throughout the water column indicating minor recirculation, but the uniform distribution indicates complete vertical mixing of the recirculated water.

4.3.4 Maximum Ebb

During maximum ebb tide (Figure 13) the thermal plume is carried to the east toward Twotree Island Channel. The 4^{0} isotherm extends up to 2,500' to the SE and extends northeast into Jordan Cove. The 6^{0} isotherm closely follows the 4^{0} isotherm while the 8^{0} isotherm shows greater areal extent than observed on previous tidal phases. The 1.5^{0} isotherm was mapped as a narrow finger extending up to 12,500' to the SE through Twotree Island Channel.

The 4^{0} and 1.5^{0} isotherms in Jordan Cove are limited to the eastern portion of the cove. No dye was detected in the northern or western parts of the cove. Vertical profiles through the plume (Figure 17) show it to have a depth of 15 to 20' within 500' offshore (Profiles ME1 and ME2). Beyond 1,000' from shore the plume as defined by the 4^{0} isotherm extends down to approximately 5' (Profiles ME3 and ME4).


NIANTIC BAY
WATERFORD, CT
N175,000
N170,000
E760,000
E770,000
JORDAN COVE
BAY POINT
Black Rock
MILLSTONE NUCLEAR POWER STATION
PLEASURE BEACH
GOSHEN
GOSHEN COVE
GOSHEN POINT
WHITE NECK POINT
Flat Rock
White Rock
Little Rock
TTIC
MP
ME1
ME2
ME3
ME4
ME5
ME6
MAGONK POINT
SEASIDE POINT
TWO-TREE ISLAND CHANNEL
Twotree Island
BARTLETT REEF
LONG ISLAND SOUND
15°
8°
4°
GRID NORTH
SCALE
1000 500 0 1000 2000 3000 Feet
LEGEND
CURRENT METER STATION
VERTICAL PROFILE POINT
4° THERMAL CONTOUR (°F)
ΔT ISOTHERM MAP
MAXIMUM EBB TIDE
MILLSTONE NUCLEAR POWER STATION
WATERFORD, CONNECTICUT
FIGURE NO. 13
DATE SURVEYED 26 AUG 87
BY P.J.LACKEY
OCEAN SURVEYS, INC.
91 SHEFFIELD ST OLD SAYBROOK CT 06475



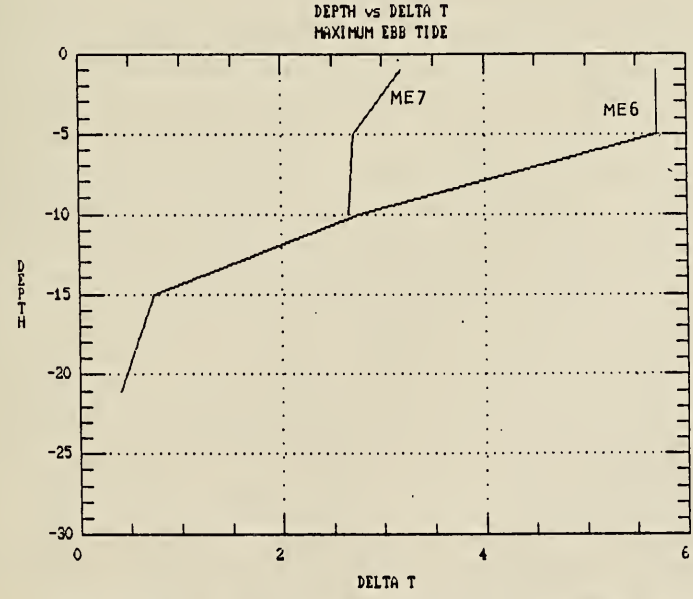


FIGURE NO. 17	DATE 9/29/87	OCEAN SURVEYS, INC.	OSI
SCALE NA	BY JAH	OLD SAYBROOK, CONNECTICUT	

At approximately 1000 hours on 26 August, Unit 1 experienced problems forcing a reactor shutdown and a partial shutdown of the circulating system. The total circulating system was operating at 94% capacity at 1200 hours resulting in a 6% reduction in the volume of water discharged at the quarry cut during the high slack tide mapping session. Discharge volume had dropped to 89% of capacity by the beginning of the maximum ebb tide mapping session at 1430. Considering the nearly ideal survey conditions, these reductions in discharge should not greatly alter the patterns and magnitudes of the thermal plume as they are presented. Adverse wind and sea conditions could be expected to have a much greater impact on the thermal plume.

4.4 Recirculation Data

Dye concentration monitoring at the Unit 1 discharge was begun at 1300 on 23 August to determine whether discharge water was recirculating back through the system. Only background levels were recorded for the first 26 hours (Figure 9) after which dye concentrations rose to approximately 0.12 ppb where they remained for the remainder of the survey. Dye concentrations at the quarry cut reached a relatively stable level 3 hours after dye injection began at 1500 on 23 August so that it took between 21 and 24 hours for dye to be sensed at the Unit 1 discharge. Dye concentrations recorded at Unit 1 equate to a temperature increase of less than $1^{o}F$ in the waters being recirculated through Unit 1. This may be an over-estimation of the actual level of thermal recirculation since radiant cooling of the water during the 21-24 hour transit time would reduce the temperature of the water without reducing the dye concentration. Mechanisms for temperature exchange should be considered with recirculation times of this length.

APPENDIX I

EQUIPMENT SPECIFICATIONS

(NOT INCLUDED: FOR THIS
INFORMATION CONTACT THE
NU ENVIRONMENTAL LAB)

APPENDIX II

TABULAR DATA

TIDE DATA
MILLSTONE POINT

23 August 1987

Time (Local)	Tide (ft)	Time (Local)	Tide (ft)
1100	2.50	1730	1.00
1130	2.40	1800	1.25
1200	2.27	1830	1.44
1230	2.18	1900	1.70
1300	2.05	1930	1.95
1330	1.81	2000	2.22
1400	1.50	2030	2.43
1430	1.20	2100	2.62
1500	1.01	2130	2.77
1530	0.88	2200	2.90
1600	0.79	2230	2.83
1630	0.76	2300	2.72
1700	0.88	2330	2.59

24 August 1987

Time (Local)	Tide (ft)	Time (Local)	Tide (ft)
0	2.35	1200	2.50
30	2.14	1230	2.24
100	1.83	1300	2.08
130	1.55	1330	1.88
200	1.20	1400	1.62
230	0.87	1430	1.33
300	0.60	1500	1.09
330	0.35	1530	0.90
400	0.16	1600	0.70
430	0.06	1630	0.63
500	-0.03	1700	0.62
530	0.07	1730	0.62
600	0.26	1800	0.85
630	0.54	1830	1.05
700	0.78	1900	1.25
730	1.10	1930	1.49
800	1.37	2000	1.76
830	1.69	2030	2.01
900	1.99	2100	2.25
930	2.23	2130	2.48
1000	2.40	2200	2.64
1030	2.57	2230	2.75
1100	2.60	2300	2.77
1130	2.60	2330	2.64

TIDE DATA
MILLSTONE POINT

25 August 1987

Time (Local)	Tide (ft)	Time (Local)	Tide (ft)
0	2.51	1200	2.40
30	2.30	1230	2.21
100	2.10	1300	2.03
130	1.85	1330	1.85
200	1.57	1400	1.60
230	1.29	1430	1.30
300	0.99	1500	1.00
330	0.70	1530	0.72
400	0.42	1600	0.55
430	0.21	1630	0.39
500	0.05	1700	0.26
530	0.00	1730	0.24
600	0.19	1800	0.34
630	0.42	1830	0.53
700	0.70	1900	0.78
730	0.98	1930	0.98
800	1.25	2000	1.25
830	1.58	2030	1.53
900	1.95	2100	1.80
930	2.20	2130	2.05
1000	2.43	2200	2.28
1030	2.55	2230	2.46
1100	2.60	2300	2.59
1130	2.56	2330	2.60

26 August 1987

Time (Local)	Tide (ft)	Time (Local)	Tide (ft)
0	2.54	1200	2.78
30	2.38	1230	2.66
100	2.15	1300	2.27
130	1.90	1330	2.27
200	1.69	1400	2.05
230	1.41	1430	1.80
300	1.08	1500	1.50
330	0.80	1530	1.26
400	0.56	1600	0.94
430	0.35	1630	0.68
500	0.15	1700	0.46
530	0.05	1730	0.26
600	0.15	1800	0.17
630	0.26	1830	0.23

26 August 1987 (Continued)

Time (Local)	Tide (ft)	Time (Local)	Tide (ft)
700	0.50	1900	0.40
730	0.78	1930	0.64
800	1.09	2000	0.86
830	1.45	2030	1.11
900	1.71	2100	1.38
930	1.99	2130	1.63
1000	2.30	2200	1.95
1030	2.50	2230	2.20
1100	2.70	2300	2.40
1130	2.78	2330	2.60

CURRENT, TEMPERATURE AND SALINITY DATA
MILLSTONE THERMAL STUDY
JORDAN COVE EAST

24 AUG 1987

TIME (EDT)	CURRENT SPEED (KTS)	CURRENT SPEED (CM/S)	CURRENT DIRECTION (DEG. TRUE)	WATER TEMPERATURE (F)	(C)	SALINITY (PPT)
1030	0.08	4.0	171	66.3	19.0	30.2
1044	0.06	3.0	159	66.0	18.9	30.2
1058	0.04	1.9	145	65.7	18.7	30.2
1112	0.04	2.3	90	65.5	18.6	30.2
1126	0.09	4.6	106	65.8	18.8	30.3
1140	0.12	6.0	124	66.0	18.9	30.3
1154	0.12	6.3	125	65.7	18.7	30.3
1208	0.11	5.8	123	65.4	18.6	30.3
1222	0.11	5.6	119	65.2	18.4	30.3
1236	0.11	5.4	114	65.1	18.4	30.3
1250	0.11	5.7	99	65.2	18.4	30.3
1304	0.24	12.1	84	65.7	18.7	30.3
1318	0.40	20.4	74	65.8	18.8	30.3
1332	0.29	14.9	77	65.4	18.6	30.3
1346	0.19	9.7	77	65.5	18.6	30.3
1400	0.26	13.5	81	65.9	18.8	30.3
1414	0.29	14.7	74	66.2	19.0	30.3
1428	0.18	9.4	87	66.6	19.2	30.4
1442	0.30	15.6	86	66.5	19.2	30.3
1456	0.32	16.4	88	67.3	19.6	30.3
1510	0.32	16.3	82	67.9	20.0	30.3
1524	0.30	15.4	86	67.8	19.9	30.3
1538	0.22	11.3	74	66.7	19.3	30.2
1552	0.17	8.8	75	66.8	19.3	30.3
1606	0.20	10.5	71	67.7	19.8	30.3
1620	0.34	17.3	69	67.1	19.5	30.2
1634	0.25	12.7	59	66.4	19.1	30.2
1648	0.20	10.2	42	66.3	19.1	30.3
1702	0.14	7.2	29	66.2	19.0	30.3
1716	0.14	7.3	32	66.4	19.1	30.2
1730	0.15	7.6	24	66.3	19.1	30.2
1744	0.13	6.8	8	66.1	19.0	30.2
1758	0.13	6.6	356	66.3	19.0	30.2
1812	0.12	6.4	336	66.3	19.1	30.2
1826	0.15	7.7	327	66.3	19.1	30.2
1840	0.19	10.0	318	66.5	19.2	30.2
1854	0.22	11.5	314	67.0	19.4	30.2
1908	0.18	9.3	286	68.0	20.0	30.3
1922	0.19	9.9	290	67.3	19.6	30.2

CURRENT, TEMPERATURE AND SALINITY DATA
MILLSTONE THERMAL STUDY
JORDAN COVE WEST

24 AUG 1987

TIME (EDT)	CURRENT SPEED (KTS)	CURRENT SPEED (CM/S)	CURRENT DIRECTION (DEG. TRUE)	WATER TEMPERATURE (F)	(C)	SALINITY (PPT)
1018	0.13	6.8	15	66.2	19.0	30.2
1032	0.10	5.3	50	66.1	19.0	30.2
1046	0.04	2.1	357	66.1	18.9	30.2
1100	0.03	1.4	306	66.2	19.0	30.2
1114	0.03	1.3	284	66.2	19.0	30.2
1128	0.03	1.6	268	66.2	19.0	30.2
1142	0.03	1.3	352	65.9	18.8	30.2
1156	0.04	2.2	7	65.8	18.8	30.2
1210	0.08	4.1	358	65.7	18.7	30.2
1224	0.13	6.8	360	65.7	18.7	30.2
1238	0.17	8.7	6	65.4	18.6	30.2
1252	0.23	11.8	9	65.8	18.8	30.2
1306	0.24	12.3	12	65.7	18.7	30.2
1320	0.25	13.1	5	65.7	18.7	30.3
1334	0.26	13.2	3	66.0	18.9	30.2
1348	0.19	9.6	358	66.5	19.2	30.2
1402	0.13	6.6	7	66.9	19.4	30.2
1416	0.12	6.4	359	66.6	19.2	30.2
1430	0.13	6.5	348	66.4	19.1	30.2
1444	0.11	5.9	345	67.2	19.5	30.2
1458	0.08	4.4	349	66.7	19.3	30.2
1512	0.08	3.9	321	66.8	19.3	30.2
1526	0.09	4.8	328	66.9	19.4	30.2
1540	0.10	5.1	319	66.7	19.3	30.2
1554	0.11	5.9	300	66.7	19.3	30.2
1608	0.16	8.3	300	67.3	19.6	30.2
1622	0.14	7.1	282	67.2	19.5	30.2
1636	0.12	6.1	307	66.9	19.4	30.1
1650	0.08	3.9	304	66.8	19.3	30.2
1704	0.06	3.0	297	66.8	19.3	30.1
1718	0.03	1.7	266	66.8	19.3	30.1
1732	0.05	2.5	244	66.8	19.3	30.2
1746	0.10	5.3	197	67.2	19.6	30.2
1800	0.17	8.7	219	68.0	20.0	30.2
1814	0.19	9.6	210	68.8	20.4	30.2
1828	0.19	9.6	202	68.4	20.2	30.1
1842	0.19	9.6	215	67.8	19.9	30.1
1856	0.17	8.6	254	67.1	19.5	30.1
1910	0.18	9.5	252	67.2	19.6	30.1
1924	0.21	10.8	244	66.7	19.3	30.1
1938	0.00	0.0		61.9	16.6	

CURRENT, TEMPERATURE AND SALINITY DATA
MILLSTONE THERMAL STUDY
JORDAN COVE EAST

25 AUG 1987

TIME (EDT)	CURRENT SPEED (KTS)	CURRENT SPEED (CM/S)	CURRENT DIRECTION (DEG. TRUE)	WATER TEMPERATURE (F)	(C)	SALINITY (PPT)
1016	0.08	4.2	338	66.3	19.1	30.1
1030	0.06	2.8	119	66.2	19.0	30.1
1044	0.11	5.6	152	66.3	19.1	30.1
1058	0.16	8.2	152	66.4	19.1	30.1
1112	0.16	8.1	160	66.4	19.1	30.2
1126	0.16	8.1	140	66.5	19.2	30.2
1140	0.14	7.4	149	66.4	19.1	30.2
1154	0.17	8.7	157	66.1	19.0	30.2
1208	0.15	7.8	128	66.0	18.9	30.2
1222	0.21	10.8	89	67.8	19.9	30.2
1236	0.22	11.3	97	67.9	20.0	30.3
1250	0.26	13.2	83	68.5	20.3	30.3
1304	0.32	16.4	91	69.1	20.6	30.2
1318	0.27	13.9	106	69.0	20.6	30.2
1332	0.25	13.1	86	68.3	20.2	30.1
1346	0.24	12.1	82	66.6	19.2	30.1
1400	0.23	11.9	69	66.4	19.1	30.2
1414	0.27	13.7	81	66.4	19.1	30.2
1428	0.32	16.6	69	66.6	19.2	30.2
1442	0.25	12.9	47	67.0	19.5	30.2
1456	0.40	20.8	77	68.3	20.2	30.4
1510	0.35	17.9	94	69.0	20.6	30.3
1524	0.23	11.8	93	69.1	20.6	30.2
1538	0.21	10.7	114	68.9	20.5	30.2
1552	0.19	9.7	112	69.0	20.5	30.2
1606	0.16	8.1	176	69.0	20.6	30.2
1620	0.14	7.3	191	69.2	20.6	30.2
1634	0.16	8.1	189	69.5	20.9	30.3
1648	0.15	7.8	216	69.8	21.0	30.2
1702	0.14	7.2	203	69.9	21.1	30.3
1716	0.13	6.5	252	69.3	20.7	30.0
1730	0.13	6.8	272	69.4	20.8	30.2
1744	0.14	7.3	304	69.0	20.6	30.1
1758	0.18	9.1	286	68.6	20.3	30.0
1812	0.19	9.6	279	69.4	20.8	30.3
1826	0.21	11.0	282	69.9	21.1	30.2
1840	0.27	13.7	268	69.3	20.7	30.1
1854	0.24	12.2	274	69.6	20.9	30.1
1908	0.23	12.0	263	69.3	20.7	30.2
1922	0.25	12.6	259	69.2	20.7	30.2
1936	0.26	13.5	271	68.1	20.1	30.1
1950	0.22	11.1	287	67.3	19.6	30.1

CURRENT, TEMPERATURE AND SALINITY DATA
MILLSTONE THERMAL STUDY
JORDAN COVE WEST

25 AUG 1987

TIME (EDT)	CURRENT SPEED (KTS)	CURRENT SPEED (CM/S)	CURRENT DIRECTION (DEG. TRUE)	WATER TEMPERATURE (F)	WATER TEMPERATURE (C)	SALINITY (PPT)
1040	0.19	9.9	53	67.7	19.8	30.1
1054	0.20	10.5	64	67.5	19.7	30.1
1108	0.29	15.0	60	68.3	20.2	30.1
1122	0.34	17.3	52	69.6	20.9	30.1
1136	0.39	20.3	49	70.2	21.2	30.1
1150	0.49	25.4	48	71.2	21.8	30.1
1204	0.51	26.5	44	71.8	22.1	30.0
1218	0.53	27.3	47	71.9	22.2	30.1
1232	0.52	26.8	41	71.4	21.9	30.0
1246	0.50	25.9	43	71.6	22.0	29.9
1300	0.48	24.7	34	71.8	22.1	29.9
1314	0.49	25.2	39	72.5	22.5	30.1
1328	0.47	24.4	44	73.1	22.8	29.9
1342	0.41	21.0	44	72.9	22.7	30.1
1356	0.31	15.9	46	72.4	22.4	30.0
1410	0.15	7.5	52	71.5	22.0	30.1
1424	0.07	3.5	15	70.2	21.2	29.9
1438	0.08	4.0	283	67.1	19.5	30.1
1452	0.10	5.0	277	67.2	19.6	30.1
1506	0.12	6.1	287	67.8	19.9	30.1
1520	0.12	6.2	272	67.8	19.9	30.1
1534	0.14	7.2	301	67.8	19.9	30.1
1548	0.14	7.2	298	67.6	19.8	30.1
1602	0.17	8.5	309	67.6	19.8	30.1
1616	0.13	6.6	290	67.8	19.9	30.1
1630	0.14	7.0	215	68.8	20.4	30.2
1644	0.13	6.6	220	69.0	20.5	30.2
1658	0.09	4.6	246	68.8	20.4	30.3
1712	0.08	4.1	232	69.3	20.7	30.2
1726	0.13	6.5	214	70.3	21.3	30.3
1740	0.16	8.4	218	70.5	21.4	30.0
1754	0.17	8.5	221	70.7	21.5	30.1
1808	0.16	8.2	217	70.9	21.6	30.0
1822	0.18	9.5	208	71.2	21.8	30.1
1836	0.18	9.1	191	70.9	21.6	30.1
1850	0.14	7.4	199	70.4	21.3	30.1
1904	0.16	8.1	210	70.4	21.3	30.1
1918	0.21	10.6	227	69.9	21.1	30.1
1932	0.36	18.5	220	70.1	21.1	30.7

CURRENT, TEMPERATURE AND SALINITY DATA
MILLSTONE THERMAL STUDY
MILLSTONE POINT

26 AUG 1987

TIME (EDT)	CURRENT SPEED (KTS)	CURRENT SPEED (CM/S)	CURRENT DIRECTION (DEG. TRUE)	WATER TEMPERATURE (F)	(C)	SALINITY (PPT)
0656	0.37	19.1	243	66.1	18.9	30.2
0710	0.48	24.5	246	68.0	20.0	30.2
0724	0.55	28.1	238	68.9	20.5	30.2
0738	0.68	35.1	243	68.2	20.1	30.1
0752	1.02	52.6	258	66.5	19.2	30.1
0806	1.16	59.6	259	66.1	18.9	30.1
0820	1.18	60.8	261	66.0	18.9	30.1
0834	1.16	59.5	265	65.9	18.8	30.2
0848	1.21	62.3	269	65.8	18.8	30.2
0902	1.28	65.9	269	65.8	18.8	30.2
0916	1.29	66.4	268	65.8	18.8	30.1
0930	1.45	74.4	265	65.3	18.5	30.1
0944	1.51	77.7	264	65.2	18.4	30.1
0958	1.54	79.0	266	65.2	18.4	30.1
1012	1.51	77.4	263	65.3	18.5	30.1
1026	1.42	73.0	263	65.3	18.5	30.1
1040	1.33	68.6	264	65.2	18.4	30.1
1054	1.25	64.2	262	65.1	18.4	30.1
1108	1.16	59.8	263	65.1	18.4	30.1
1122	1.07	55.2	264	65.1	18.4	30.2
1136	0.96	49.3	267	65.0	18.3	30.2
1150	0.83	42.9	267	64.9	18.3	30.2
1204	0.61	31.4	281	65.2	18.4	30.2
1218	0.25	12.9	322	65.8	18.8	30.0
1232	0.24	12.2	27	66.0	18.9	30.0
1246	0.38	19.5	44	66.0	18.9	30.0
1300	0.55	28.5	51	66.1	18.9	30.0
1314	0.66	33.8	67	67.6	19.8	30.2
1328	0.58	29.7	75	67.7	19.8	30.1
1342	0.77	39.6	67	67.3	19.6	30.1
1356	0.80	41.1	75	66.9	19.4	30.2
1410	0.87	44.9	65	66.5	19.2	30.1
1424	0.91	47.1	74	66.3	19.0	30.1
1438	1.00	51.5	69	66.3	19.0	30.1
1452	1.02	52.5	78	66.8	19.3	30.2
1506	1.06	54.3	76	67.0	19.4	30.2
1520	1.06	54.6	80	66.7	19.3	30.1
1534	1.09	55.9	69	66.8	19.4	30.1
1548	1.09	56.1	69	66.8	19.3	30.1
1602	1.09	56.0	73	66.5	19.2	30.1
1616	1.00	51.5	73	66.3	19.1	30.1
1630	0.95	48.8	69	66.2	19.0	30.1

CURRENT, TEMPERATURE AND SALINITY DATA
MILLSTONE THERMAL STUDY
TWOTREE ISLAND CHANNEL

26 AUG 1987

TIME (EDT)	CURRENT SPEED (KTS)	CURRENT SPEED (CM/S)	CURRENT DIRECTION (DEG. TRUE)	WATER TEMPERATURE (F)	(C)	SALINITY (PPT)
0706	0.41	21.0	301	66.8	19.4	30.1
0720	0.53	27.4	297	66.4	19.1	30.1
0734	0.50	25.7	304	66.3	19.1	30.1
0748	0.59	30.3	293	66.4	19.1	30.0
0802	0.77	39.8	288	66.4	19.1	30.1
0816	0.91	47.1	284	66.6	19.2	30.1
0830	0.98	50.5	280	66.6	19.2	30.1
0844	1.04	53.4	290	66.6	19.2	30.1
0858	0.94	48.6	288	66.5	19.2	29.9
0912	0.90	46.3	283	66.5	19.2	29.8
0926	0.78	40.1	283	66.3	19.1	29.8
0940	0.77	39.6	280	66.0	18.9	29.8
0954	0.78	40.3	290	65.9	18.8	29.7
1008	0.78	40.1	286	65.8	18.8	29.7
1022	0.75	38.8	292	65.6	18.6	29.8
1036	0.74	38.1	293	65.4	18.6	29.7
1050	0.12	6.4	295	65.3	18.5	29.7
1104	0.00	0.0	290	65.3	18.5	29.8
1118	0.21	11.0	299	65.3	18.5	29.8
1132	0.42	21.8	292	65.3	18.5	29.7
1146	0.33	17.0	300	65.2	18.4	29.9
1200	0.26	13.2	298	65.3	18.5	30.0
1214	0.12	6.4	326	65.5	18.6	30.2
1228	0.12	6.2	149	66.1	18.9	30.2
1242	0.26	13.5	125	66.2	19.0	30.1
1256	0.42	21.6	135	66.3	19.0	30.1
1310	0.63	32.3	106	68.2	20.1	30.2
1324	0.69	35.6	96	68.4	20.2	30.0
1338	0.76	38.9	98	67.6	19.8	30.0
1352	0.91	46.7	97	67.2	19.6	30.1
1406	1.17	60.3	101	67.8	19.9	30.1
1420	1.25	64.3	94	67.8	19.9	30.1
1434	1.23	63.5	93	67.8	19.9	30.1
1448	1.25	64.4	97	68.7	20.4	30.1
1502	1.15	59.1	108	68.6	20.3	30.1
1516	1.14	58.5	113	68.7	20.4	30.1
1530	1.13	58.2	110	68.5	20.3	30.1
1544	1.07	54.9	114	69.0	20.5	30.1
1558	1.00	51.5	114	69.0	20.6	30.1
1612	0.87	44.8	116	69.0	20.5	30.0

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